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Dose and Noise in Abdominal Computed Tomography Examinations

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Summary

Background: Dose reduction in computed tomography (CT) examinations was an idea of the Co-ordinated Research Project (CRP) "Dose Reduction in Computed Tomography (CT) while maintaining Diagnostic Confidence", supported by the International Agency of Atomic Energy (IAEA) in the years 2003-2005. Participation in the CRP inspired the authors' attempts to elaborate a method for optimization of CT abdominal procedures allowing reduce a dose to patient with saving diagnostically satisfying image quality. The paper presents the algorithm together with clinical verification of the results of the study.

Material/Methods: Two types of single-slice CT scanners were used for the investigations. The images recorded for patients undergoing routine abdomen examinations and then these obtained with modified exposure parameters were analyzed. The influence of the changed tube outputs on image quality was checked using Catphan 424 phantom.

Results: As the result no statistically significant difference between the measured noise in clinical images for patients examined at routine and modified settings (within the same weight category) was observed.

Conclusions: The conclusion was that at routine (screening) abdomen examinations, the dose may be reduced up to 50% with saving diagnostically satisfying image quality.

Key words: **CT • image quality • doses • patients**

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Background

Optimization of medical exposures is a legislative requirement stated in EC Directive 97/43 [1], and putting this principle into common practice is of particular importance in high-dose and intensively used procedures. To this end, great attention is paid to optimization of computed tomography (CT) procedures, and namely to reduction of doses to patients while saving a satisfactory image quality [2-6].

Over the recent years, dose reduction in CT examinations has been the subject of relatively frequent discussions, mostly due to a remarkable increase in the use of CT and a growing share of CT examinations in collective effective dose, reaching 30-40% for certain groups of population [7]. This is especially important in relation to multi-detector scanners (MDCT), which need a high intensity of primary x-ray beam to collect the projection data so fast. That is why large CT companies equip their products with software including options of "patient dose saving" (AutomA and Smartscan by GE Medical Systems, CARE Dose by Siemens [8]). By automatic adjustment of tube current to follow changing sizes (volume) of patients, the desired noise level on the projection can be maintained and the dose reduced up to 25% [9,10]. The effectiveness of tube current modulation depends on the shape of the scanned object: if the diameter (AP or LAT) is not visibly varied (e.g. the man's abdomen), the obtained reduction will not be substantial.

Another way to obtain dose reduction is "manual control" of x-ray intensity, which means the proper selection of exposure settings to meet the needs of the given diagnostic case (or category of cases). This occurs when a small object is scanned, or anatomical details (lesions) easy to differentiate from the background (i.e. neighbouring tissues) are detected.

The first situation means that a small volume acquires low intensity of x-ray, and then tube output should be related to the mass of the patient or to his/her cross-section (in the scanned plane). Such solutions are frequently used for pediatric patients [11], but also for abdominal CT in adults [12]. Especially for patients with weight lower than 80 kg, the dose reduction up to 50% was reported at acceptable image quality.

The other situation is the selection of exposure settings necessary for a special type of lesions in the body, on the basis of theoretical evaluation of their attenuating properties and then checking the selection experimentally, through phantom measurements [13]. That is a proposal for head CT (sinuses mainly) [14–17], chest CT scanning [18, 19], CT colonography [20] or CT for urinary tract calculi [21].

In contrast to the auto-modulation method, in the aforesaid situations, the exposure settings (mAs) are kept constant during the whole examination. The "manual control" is a solution available for both MDCT and single-slice CT scanners.

In this paper, a method for optimisation of abdominal CT procedures is presented together with the results of its implementation for two single-slice scanners. This method is a sub-type of the "manual control" solutions discussed above.

Image noise is one of the main indicators of image quality (together with low-contrast resolution and high-contrast resolution) and its level in clinical images is influenced not only by technical factors, but also by cross-section (in the scanned plane) and attenuating features of the scanned object. On the other hand, quality of clinical images should fulfil diagnostic needs, and the highest quality is not absolutely necessary in every case. Thus, to establish some recommendations on exposure settings with additional requirements concerning the noise level seems to be a good way to optimise a CT procedure. The aim of the method described in the paper is to give such proposal for abdominal CT procedure.

This idea covers the aim of the Co-ordinated Research Project (CRP) "Dose Reduction in Computed Tomography (CT) while maintaining Diagnostic Confidence", supported by the International Agency of Atomic Energy (IAEA) in the years 2003-2005.

Participation in the CRP inspired the authors' attempts to elaborate an algorithm, which bears the name of the "scanner estimation method" (SE-method).

Materials and methods

All the investigations concerned routine abdominal CT procedures performed in adult patients on two types of CT scanners.

The images were analyzed during real patients' examinations. The patients were examined mainly due to suspected metastases and malfunction of the liver and pancreas.

The main stages of the investigations were as follows:

1. to evaluate the noise-to-mass dependence for the particular scanner on a routine abdomen procedure offered by its software (i.e. the primary of dependence: $\sigma_0(M)$),

2. knowing the $\sigma_0(M)$ function, to modify exposure parameters of the scanner for dose reduction,

3. to perform the patients' examinations at modified exposure parameters (following the approval of the Ethics Committee) and to evaluate the clinical images,

4. to carry out a general evaluation of the results and possibilities of their implementation into the routine diagnostic practice.

Patients' images for evaluation were chosen in the first examination phase (prior to contrast medium application), taking three consecutive slices of the well-visible liver. The circular regions of interest (ROI) of about 100 cm^2 were selected for segments VI and VIII of the right liver lobe, and their Cartesian coordinates were kept constant for the three consecutive slices. The mean values of CT number and its standard deviation (SD) (both the quantities in Hounsfield units) for the particular ROIs are recorded: CT value was interpreted as contrast of the image and SD was understood as the noise level. All the values recorded for the particular patient were taken into account in calculating the arithmetic mean values of CT and SD.

The general quality of the images collected for a given patient from the diagnostic point of view was evaluated by a radiologist according to a five-point scale.

All the data concerning the patient, i.e. body mass, AP and LAT diameters, scanned length and the exposure parameters, were recorded using a special form.

The data were collected and analyzed for the statistically satisfying number of patients with body mass ranging from 40 to over 100 kg, providing the basis for the evaluation of the primary noise-to-mass dependence ($\sigma_0(M)$) for the given CT scanner (by MS Excel).

Dose reduction planning relies on defining the tube outputs (mAs) appropriate for the patient's mass, at which noise levels in diagnostic images can be regarded as acceptable. Since the level of noise for obese patients is generally higher than that for slim ones and the images satisfied diagnostic requirements, the planning of dose reduction was based on the concept that the noise level for slim patients could significantly increase, whereas it should not increase for really obese patients.

Generally, in the SE method the following schedule is applied:

1) to keep routine value of voltage constant (U=const.),

2) to estimate $\sigma_0(M)$ on the basis of images performed at the routine protocol,

3) to calculate $\sigma_0(50)$ and $\sigma_0(100)$ from the aforesaid relationship,

4) to plan dose reduction assuming that the dose to a 50-kg patient should be 2 times lower and that to a 100-kg patient should not be changed;

5) the above assumption determines the expected noise levels (i.e. the noise for a 50-kg patient should increase by about 40% and that for a 100-kg patient should not be changed) and then modified dependence between noise level and patient's mass ($\sigma(M)$) and, consequently, the suggested values of tube output (mAs),

6) the suggested mAs values have to be compared with available settings of CT scanner, and the values closest to the theoretically computed ones should be chosen.

Before the beginning of any modifications of settings, the influence of the changed tube outputs on image quality was checked using a Catphan 424 phantom. The low-contract resolution was regarded as a main indicator of image quality, however, the high-contrast resolution was also analyzed.

For a dosimetric evaluation of particular exposure parameters, volumetric computed tomography dose index ($CTDI_{vol}$) was calculated on the basis of measurements using a NOMEX (PTW Frieburg) with the ionization pencil chamber and a PMMA "BODY" 5-hole phantom.

Results

The experiment with the patient's dose reduction was performed for 2 single-slice CT scanners: a Picker PQ-5000 and a Siemens Somatom AR-Star. PQ, the fourth generation scanner, operating since 1995, participating in the CRP. AR, the third generation scanner, working since 1997, was not included in the CRP. The primary set of the data for PQ was collected under the framework of the CRP, and the appropriate data for AR were completed independently. Patients' examinations were performed after approval by the Ethics Committee at Nofer Institute of Occupational Medicine: Decision No. 22/2005.

A. Results for PQ-5000

The parameters of "routine adult abdomen" are as follows:

Spiral mode, pitch 1.5, U=120kV, I=250 mA, t=1s, slice collimation SC=10 mm (for selected cases SC= 8 mm).

These parameters are used for all the adult patients, independently of their body mass.

For these settings, there were the following values of $CTDI_{vol}$:

$CTDI_{vol}$= 20.4mGy at SC=8 mm and

$CTDI_{vol}$=16.3mGy at SC=10 mm

The primary noise-to-mass dependence for PQ was obtained on the basis of measurements performed for 50 patients.

The values are given in Table 1.

The noise-to-mass dependence, evaluated on that basis, was:

$$\sigma_0(M) = 0.11M + 3.00 \text{ (Pearson's coefficient } R^2=0.2864), \quad (1)$$

then $\sigma_0(50)=8.5$ and $\sigma_0(100)=14$.

According to the aforesaid assumptions of the SE method, exposure parameters should be modified to obtain the noise levels of:

$\sigma_0(50) \approx 1.4\ \sigma_0(50)$ and $\sigma(100) \approx \sigma_0(100)$.

Thus, $\sigma(50)=12$ and $\sigma(100)=14$.

The new noise-to-mass dependence resulting from the above statements is

$$\sigma_0(M) = 0.04M + 10.00. \quad (2)$$

Keeping tube voltage constant (like the slice collimation and pitch), the proposed tube output should result from the noise changes according to the formula [22] given below:

$$Q = Q_0\left(\frac{\sigma_0}{\sigma}\right)^2 \quad (3)$$

The values of tube outputs calculated in this way for PQ-5000 and those suggested by the CRP scientific

Table 1. The noise level measured in ABDOMEN images obtained at routine set of exposure parameters for PQ-5000.

Body mass category [kg]	Number of patients	Mean mass(*) m[kg]	Mean value of noise measured at the liver [HU]
26-45	1	40	5.7
46-65	21	56.4±5.2	9.7±1.4
66-85	19	76.4±5.7	10.7±3.2
86-105	9	90.1±4.3	13.6±3.5
>105	1	108	18.8

(*) Mean mass is the arithmetic mean value calculated for the patients classified to the particular body mass category.

Table 2. The modification of tube outputs and the resultant change of noise levels for particular body mass categories.

Mass [kg]	σ_0	σ (expected)	Tube output [mAs]	
			by SE-method	according to M. Prokop(*)
50	8.5	12.0	125	129
60	9.6	12.4	150	160
70	10.7	12.8	175	191
80	11.8	13.2	223	223
90	12.9	13.6	237	254
100	14.0	14.0	250	285

(*) After adaptation to actually available values according to scanner software.

consultant Prof. M.Prokop on the basis of general data collected under the CRP framework are given in Table 2.

The results of low-contrast resolution in dependence on tube current and time per tube rotation for the analyzed PQ-5000 are presented in Table 3.

The same phantom studies show that high-contrast resolution (defined as the smallest differentiable gap in high-contrast section of the phantom) does not change at the proposed settings, and remains at a constant level of 0.6-0.7 mm at the standard kernel function.

Since no visible lowering of image quality was found for phantom images, clinical verification of the proposed changes in exposure parameters was begun.

To verify how noise in clinical images is affected by the proposed modification of tube outputs, diagnostic abdominal CT examinations were performed for the patients of two mass categories: 50-60 kg and 70-80 kg. In view of a wide range of available settings offered by PQ-5000, two sets of modified parameters, resulting in similar tube outputs, were tested for each group of patients, and for both of them the noise levels were compared with those at routine settings. The details are shown in Table 4.

The results presented above were evaluated statistically, using one-way analysis of variance. This allowed comparing natural divergence of measurements in particular groups with variance between these groups resulting from the differences between the used exposure parameters.

Snedecor - Cochran test statistics were calculated and then compared with the critical value corresponding with the selected significance level and degrees of freedom. The results are given in Table 5.

$F_{observation} << F_{critical}$ ($\alpha=0.05$) means no statistically significant difference between the noise values measured in the particular groups, which were exposed at different tube outputs.

In consequence, the quality of clinical images was not affected by the reduction of tube output in relation to the routine value (setting).

Table 3. Low-contrast resolution at different exposure parameters evaluated with Catphan 424 measurements for PQ-5000 (SC=10 mm).

Exposure parameters		$CTDI_{vol}$ (*) [mGy]	Visualization of low-contrast objects at the nominal contrast of 1%	
			Measured contrast level [%]	The diameter of the smallest detectable object [mm]
120 kV,	250 mA, 1.0 s	16.3	0.94	3
	150 mA	10.0	1.04	3
	100 mA	6.6	0.87	4
	65 mA	4.3	0.86	3
120 kV,	150 mA, 1.5 s	15.0	0.99	3
	100 mA	10.0	1.01	3
	65 mA	6.6	1.05	3
120 kV,	125 mA, 2.0 s	16.3	0.93	2
	65 mA	8.8	1.11	3

(*) measured with the use of a PMMA "BODY" phantom.

Table 4. Noise levels measured in the diagnostic abdomen images for particular groups of patients at routine and modified settings.

Mass[kg]/No of patients	Tube output [mAs] / Noise [HU]	Number of patients	Tube output [mAs] / Noise [HU]	Number of patients	Tube output [mAs] / Noise [HU]	Number of patients
50-60 (33)	250mA*1s Routine	10 (*2)	150mA*1s Modified 1	13 (*1)	100mA*1.5s Modified 2	10 (*1)
	10.15±2.40		11.26±2.16		11.69±1.68	
70-80 (38)	250mA*1s Routine	13 (*3)	150mA*1.5s Modified 1	11	200mA*1s Modified 2	14 (*4)
	13.32±2.27		13.43±1.19		13.34±1.65	

(*) denotes the number of cases with the score below maximum (i.e. 5) or with a number of artefacts (i.e. bright bands).

Table 5. Statistical evaluation of the noise results for patients examined with the use of PQ-5000.

Mass [kg]	Degrees of freedom	$F_{critical}$ (α=0.05)	$F_{observation}$
50-60	r_1=2, r_2=30	2.49	0.1360
70-80	r_1=2, r_2=35	3.25	0.0011

α – significance level

B. Results for AR-Star

There are the following parameters of "routine adult abdomen":

spiral mode, pitch 1.0, U=130kV, I=83 mA, t=1.9s, slice collimation SC = 10 mm.

These parameters are used for all the adult patients, independently of their body mass.

For these settings $CTDI_{vol}$=21.3mGy at SC=10 mm.

The primary noise-to-mass dependence for AR-Star was established on the basis of measurements performed for 27 patients.

The detailed numbers are given in Table 6.

The noise-to-mass dependence, evaluated on that basis was:

$\sigma_0(M) = 0.19M - 4$ (Pearson's coefficient R^2=0.7975), (4)

then $\sigma_0(50)=5.5$ and $\sigma_0(100)=15$.

According to the assumptions of the SE-method, exposure parameters should be modified to obtain the noise levels of:

$\sigma(50) \approx 1.4\ \sigma_0(50)$ and $\sigma(100) \approx \sigma_0(100)$.

Because of rather limited combinations of settings available from the software of AR-Star, the above assumptions were slightly changed to:

$\sigma(50) \approx 1.3\ \sigma_0(50)$ and $\sigma(100) \approx \sigma_0(100)$,

thus, the expected values are $\sigma(50) \approx 7$ and $\sigma(100) = 15$.

The new noise-to-mass dependence resulting from the above statements is then

$$\sigma(M) = 0.16M - 1 \quad (5)$$

On this basis, the expected values of tube output were calculated.

Table 6. The noise level measured in ABDOMEN images obtained at the routine set of exposure parameters for AR-Star.

Body mass category [kg]	Number of patients	Mean mass(*) m[kg]	Mean value of noise measured at the liver [HU]
50-59	5	53.4±3.6	6.7±0.8
60-69	7	64.1±1.6	8.2±1.6
70-79	6	71.8±2.1	10.3±1.0
80-89	5	83.0±2.8	11.0±2.5
90-102	3	95.7±6.0	14.5±2.7
>105	1	117	25.7

(*) The arithmetic mean value calculated for the patients classified to a particular body mass category.

Table 7. Low-contrast resolution at different exposure parameters for AR-Star (SC=10 mm).

Exposure parameters (SC=10mm)		$CTDI_{vol}$ [mGy]	Visualization of low-contrast objects at the nominal contrast of 1%	
			Measured contrast level [%]	The diameter of the smallest detectable object [mm]
130 kV,	83 mA, 1.5 s	16.8	1.12	3
	63 mA, 1.5 s	12.8	1.18	3
130 kV,	83 mA, 1.9 s	21.3	1.17	2
	63 mA, 1.9 s	16.2	1.26	3

Table 8. The noise levels expected and measured at ABDOMEN images obtained at modified set of exposure parameters for AR-Star scanner.

M[kg]	σ_0 (M) [HU]	Tube –output [mAs]		k (*)	Noise predicted at modified settings [HU]		Noise measured at modified settings [HU]	Number of patients and range of masses in the noise measurements (for modified settings)
		calculated (Q_{calc})	really selected (Q_{real})		σ(M)	σ'(M)=k. σ(M)		
50	5.5	99	95	1.02	7.0	7.1	9.0±1.2	8: 45-54
60	7.4	118	95	1.11	8.6	9.5	9.3±2.2	7: 55-64
70	9.3	133	95	1.18	10.2	12.0	11.9±1.9	7: 65-74
80	11.2	144	120	1.10	11.8	13.0	13.2	1: 75-84
90	13.1	153	120	1.13	13.4	15.1	16.7±3.9	4: 85-94
100	15.0	160	120	1.15	15.0	17.3	18.5	1: 95-104

$$k = \sqrt{\frac{Q_{calc}}{Q_{real}}}$$

The relation between low-contrast resolution and exposure settings for AR-Star was also checked, using a Catphan 424 phantom, along with $CTDI_{vol}$ evaluation on the basis of measurements performed with the use of a PMMA "BODY" phantom. The results are presented in Table 7.

Low-contrast resolution of phantom images was practically not lowered, therefore, clinical verification of proposed changes in exposure settings was started. The high-contrast resolution at the standard kernel function was also constant at about 0.8 mm.

The detailed results of the expected and measured noise levels in abdominal images obtained for an AR-Star scanner are presented in Table 8.

These results were also analyzed statistically, using the test for two arithmetical mean values taken from independent probes with statistic of Student's t-test. The details are shown in Table 9.

Discussion

The results of the SE method implementation obtained for the two technically different CT scanners also differ to each other. The noise-to-mass dependence for modified settings (σ(M)) of PQ-5000 is nearly flat, which means a nearly constant level of noise in the patients' abdominal images with practically no relation to the patients' weight (within the range of (50-100) kg).

Table 9. Statistical comparison of noise levels in abdominal images at routine and modified exposure settings for AR Star.

Weight category [kg]	Routine settings		Modified settings		$t_{Student}$	No. of freedom degree	$t_{critical}$
	No.	$\sigma_0 \pm$S.D. [HU]	No.	$\sigma \pm$S.D. [HU]			
45-54	3	6.4±0.8	8	9.0±1.2	3.44	10	2.2228
55-64	5	8.0±1.5	7	9.3±2.2	1.11	10	2.2228
65-74	9	9.4±1.8	7	11.9±1.9	2.76	14	2.145
75-84	4	9.3±0.4	1	13.2	8.87	3	>2.571
85-94	3	13.4±1.3	4	16.7±3.9	1.37	5	2.571
95-104	3	16.9±3.9	1	18.5	0.35	2	>>2.57

S.D. – standard deviation

In contrast, inclination of the σ(M) function for AR-Star is significantly greater, which probably means that the intensity of x-rays is still too high for small objects and, therefore, the noise level for them can be kept relatively low. To obtain its increase, a significant decrease of tube-output is necessary, which is not allowed by the present version of the scanner software. The conclusion agrees with an "over-noise" observed for the thinnest patients (below 50kg) in comparison with the predicted level.

Probably a large amount of radiation is scattered on bones, and absence of fat layer as an absorber is the reason for high noise level. For the remaining group of patients, the measured noise values are in good agreement (within the range of error) with the predicted ones.

An additional observation comes from the results for PQ-5000, where the patients were exposed at modified settings resulting in nearly the same tube output obtained by two Ixt [mAs] combinations. That was for checking how far the noise level is influenced by the time of tube rotation, because in another study performed also for a PQ scanner it was concluded that low-contrast resolution slightly decreases when the time per scan is shorter [23]. (The same can be concluded from the data in Table 3.) However, no statistically significant difference between the measured noise in clinical images for patients examined at routine and modified settings was observed (within the same weight category). Since the intensity of primary x-ray beam does not change in practice, these findings confirm the theory. Probably in this case the change of time per rotation from 1 s to 1.5 s for patients of (50-60) kg was too small to influence the diagnostic value scored by a radiologist.

To summarize, a benefit resulting from the SE method is dose reduction of about 40% for slim patients (about 50 kg), the while quality of images is still diagnostically satisfying. For more corpulent patients, the reduction is lower: (10-25)% depending on the scanner.

These findings agree with the published opinions cited in "Introduction" that for slim patients (about 50 kg) undergoing CT abdominal procedures, the dose reduction up to 50% was reported at acceptable image quality [12].

Conclusions

1. The SE method can be used for any CT scanner, however it can be especially useful for single-slice scanners without automatic modulation of tube output.

2. The SE method seems to be a useful tool for dose reduction while keeping the quality of image under control. This is especially true for abdominal examinations performed on a single-slice CT scanner.

3. On routine (screening) abdominal examinations, the dose may be reduced up to 50% with preserved diagnostically satisfying image quality.

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