

Extent of simultaneous radiation dose and iodine reduction at stable image quality in computed tomography of the chest

A systematic approach using automated tube voltage adaption and iterative reconstructions

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Abstract

Background: Aim of this study was to systematically combine tube voltage adaptation and iterative reconstructions for reduction of iodine and radiation dose.

Methods: Settings for the study protocol were evaluated in ex-ante trials to provide image quality that is comparable to a reference protocol at 120kV with tube current modulation. Consecutive patients were randomized to undergo computed tomography (CT) of the chest using the study protocol (n=62) or reference protocol (n=50). Objective and subjective image quality was assessed and compared.

Results: Tube voltage was decreased to 100kV in 47 patients and to 80kV in 15 patients in the study group. The iodine dosage (16.1 vs 10.5g) and the effective radiation dose (3.6 vs 2.5mSv) were significantly decreased in the study group (both $P < .001$). Contrast-to-noise ratio was comparable in the pulmonary trunk and increased in the aorta ($P < .01$). Subjective image quality was comparable without statistically significance.

Conclusions: Simultaneous reductions in iodine dosage and radiation dose by one-third are feasible for CT of the chest.

Abbreviations: AV = attenuation value, BMI = body mass index, CM = contrast media, CNR = contrast-to-noise ratio, CT = computed tomography, CTDI_{vol} = volumetric CT dose index, DLP = dose length product, ED = effective dose, FBP = filtered back projection, HU = Hounsfield units, IR = iterative reconstruction, ROI = region of interest, SD = standard deviation, SNR = signal-to-noise ratio, TCM = tube current modulation, TVA = tube voltage adaptation.

Keywords: adaptation, chest, computed tomography, contrast media, iterative reconstruction, radiation dose, tube voltage

1. Introduction

Computed tomography (CT) is the modality of choice for a broad range of indications. Combined evaluation of the lungs and the mediastinal structures is often indicated in oncologic patients and can be achieved by i.v. contrast media injections. The broad availability and rapid technological evolution of CT are leading to a steadily increasing number of indications and examinations.^[1] However, the adverse effects of ionizing radiation and iodinated contrast media (CM) are ongoing reasons for concern.

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According to the linear-no-threshold model in cancerogenesis by ionizing radiation,^[2] radiation dose has to be kept as low as reasonably achievable (ie, the ALARA principle).^[3–5] Intravenous application of iodised CM might impair renal function and induce a hypersensitivity reaction or thyrotoxic crisis.^[6,7] A correlation between the extent of CM-induced nephropathy and CM dose has been reported in literature.^[8]

Several technical solutions have been proposed to achieve a substantial radiation dose reduction while maintaining image quality on a diagnostic level. Online tube current modulation (TCM) with respect to patient geometry is widely implemented in routine protocols.^[9] Reduction of the tube voltage decreases the radiation dose and increases the image contrast, with the shortcoming of increased image noise.^[10] Hence, automated tube voltage adaptation (TVA) algorithms were designed to individually combine adjustment of the tube voltage and the tube current using attenuation information from the localizer to provide an optimum for both radiation dose reduction and contrast-to-noise ratio (CNR) for each individual.^[11,12]

However, the increased image contrast obtained by reduced tube voltages in CM-enhanced CT additionally offers the opportunity for reduction of the CM dosage by reducing the iodine delivery rate.^[13] But most x-ray tubes are unable to completely compensate for the increased image noise at reduced tube voltages by increasing the tube current. Therefore, iterative

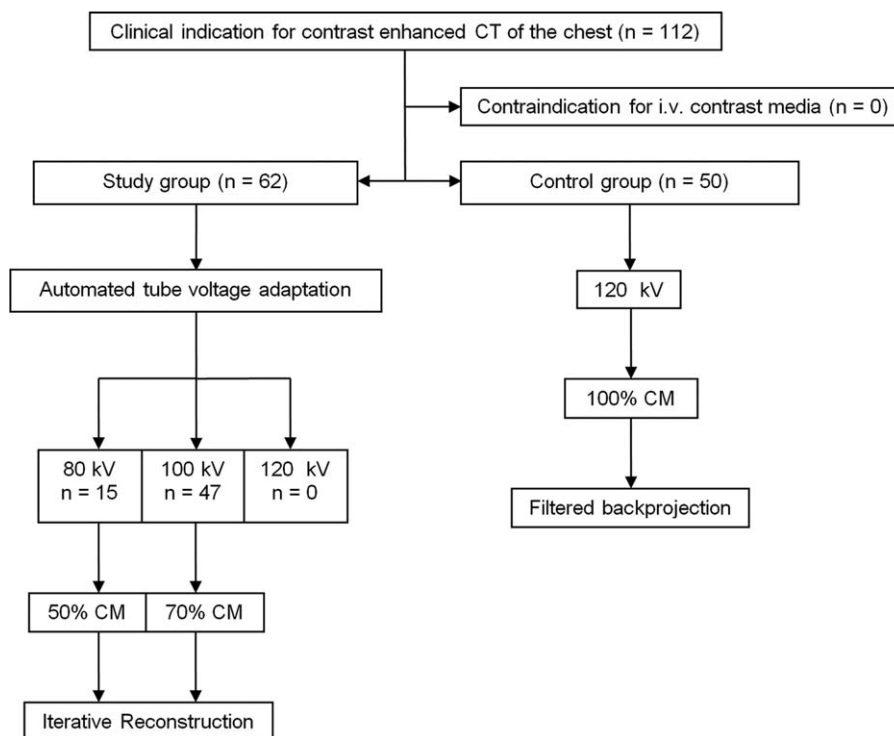


Figure 1. Flowchart of the study design.

reconstruction (IR) algorithms have been used to balance the image noise in examinations with reduced tube voltages and reduced CM dosage. They have proven their ability to substantially decrease the image noise at a given radiation dose and can therefore be used to obtain diagnostic image quality even at reduced radiation exposures.^[14]

The wide range of individual settings for the TVA and IR algorithms means that it is challenging to find a combination that provides a well-balanced mixture of the advantages of each algorithm in clinical routine. The aim of this study was therefore to find an examination protocol for CM-enhanced CT of the chest that provides a consistent image quality compared with a reference at 120kV, and individually reduces the radiation exposure and CM dosage using the latest techniques with a minimum of complexity for medical staff in clinical routine.

2. Materials and methods

2.1. Patients

This prospective, single-center study was performed under an institutional review board-approved protocol and complies with the Declaration of Helsinki. Written informed consent was obtained from each individual. In all, 112 subsequent patients with a clinical indication for CM-enhanced CT of the chest was enrolled over a time period of 3 months and randomly assigned either to the reference (A: n=50) or study group (B: n=62) without restrictions by the radiographer using simple coin toss. Body mass index (BMI) was calculated as body weight divided by the square of body length.^[15] All examinations were performed on a 128-slice second-generation Dual-source CT scanner (SOMATOM Definition Flash, Siemens Healthineers GmbH, Forchheim, Germany) equipped with an anatomy-based automated TCM algorithm (CARE dose, Siemens Healthineers

GmbH, Forchheim, Germany), an automated TVA algorithm (CARE kV, Siemens Healthineers GmbH, Forchheim, Germany) and a raw data-based IR algorithm (SAFIRE, Siemens Healthineers GmbH, Forchheim, Germany). Patients with a history of allergic reaction to iodised CM, renal insufficiency (glomerular filtration rate ≤ 45 mL/min/1.73 m²) or hyperthyroidism were excluded in advance (Fig. 1).

2.2. CT technique

Phantom measurements with a dilution series of iodinated contrast media (Iomeprol, Imeron 350, Bracco Imaging, Konstanz, Germany) were performed ex ante at 120, 100, and 80kV to determine the concentration that provided comparable attenuation of the probes at decreased tube voltages compared with a 100% probe (0.35 g/mL) at 120kV. Detailed results are shown in Table 1.

The reference image noise was assessed to be 16.0 ± 2.7 Hounsfield units (HU) in an ex ante collective (n=18, median

Table 1

Phantom measurements.

	120kV	100kV	80kV
100%	342	455	634
90%	307	413	564
80%	268	383	466
70%	229	352	423
60%	208	297	371
50%	170	255	320
40%	131	170	232
30%	91	144	190

Attenuation values (HU) for dilution series at different tube voltages. Values in proximity of the 100% (3.5 mg/mL iodine) probe at 120kV are bold-printed.

Table 2

Retrospective simulation of tube settings and calculated radiation exposure (estimated CTDI_{vol}) for different iodine weightings of the tube voltage adaptation algorithm (TVA).

TVA level	1	2	3	4	5	6	7	8	9	10	11	12
Tube voltage, kV	120	120	120	120	100	100	100	100	80	80	80	80
Tube current, mAs	102	102	105	113	145	153	144	152	185	200	201	200
Est. CTDI _{vol} , mGy	6.9	6.9	6.9	6.9	6.7	6.3	5.9	5.7	5.2	4.8	4.3	3.9
Rel. exposure, %	100	100	100	99	96	91	87	83	77	70	62	56

The relative exposure is referred to a protocol using 120 kV and tube current modulation without TVA. Values are given as median. The matching result for the study protocol is printed in bold-type. CTDI_{vol}=volumetric computed tomography dose index.

BMI=25.7 kg/m²) examined with our institutional standard protocol for chest CT (fix tube voltage 120 kV, TCM with 100 ref. mAs, pitch=0.8, slice acquisition=128 × 0.6 mm, gantry rotation time=0.5 seconds) in an aortopulmonary angiographic phase after intravenous CM injection (volume=46 mL, flow=2 mL/s, delay=30 seconds) by measurement of the standard deviation (SD) of the attenuation values (AVs) in the pulmonary trunk and the aortic root.

Different iodine weightings (grades 1–12) of the TVA algorithm and their impact on the estimated radiation exposure, given as a volumetric CT-dose index (est. CTDI_{vol}), were retrospectively simulated on a CT simulation console (AWP, Siemens Healthcare, Forchheim, Germany) using the localizers from the ex-ante collective as input (Table 2, Fig. 2A).

All datasets from the ex ante collective were reconstructed as follows to evaluate the IR level that is needed for compensation

for the increased image noise by the estimated reduction of radiation dose: first, by using a standard filtered back projection (FBP) kernel (B41) and second, using all available levels (1–5) of an IR algorithm (SAFIRE, Siemens Healthineers GmbH, Forchheim, Germany). Their impact on image noise was measured as differences in SD of the AVs in the pulmonary trunk and the aortic root. The results are given as relative image noise in Table 3. Reduction of image noise was calculated to be about 11% by each IR level compared with FBP. The minimum relative exposure that was needed to obtain image noise levels smaller than or equal compared with the full dose/FBP references were calculated for each IR level following the given physical inversely proportional relationship of image noise and square root of radiation dose in FBP (Table 3, Fig. 2B).

Comparison with the results of TVA simulation yielded a combination of TVA grade 8 and IR level 1 or TVA grade 11 and

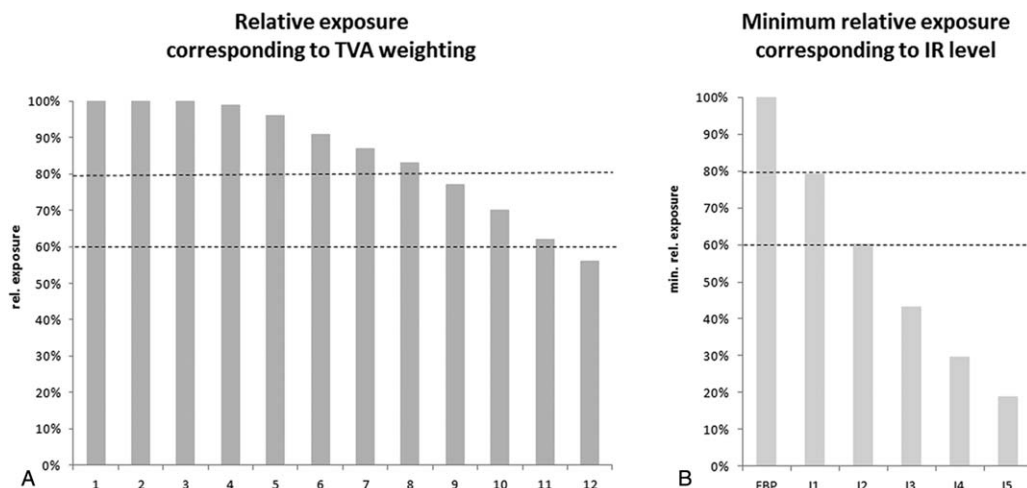


Figure 2. Ex ante evaluation of the study protocol. Relative radiation dose for different iodine weightings of the tube voltage adaptation (TVA) algorithm (1–12) compared with the reference without TVA as estimated by ex ante simulations in a reference collective (A). Relative image noise for different levels of the iterative reconstruction (IR) algorithm (1–5) compared to filtered back projection (FBP) reconstructions in the reference collective. The minimum relative radiation exposure that would be needed to obtain image noise levels smaller than or equal compared to the full dose/FBP references were then calculated for each IR level (B). Comparison with the exposures obtained in (A) resulted in the equivalence hypothesis using TVA weighting 8 and IR level 1 for the study protocol. The alternative protocol using TVA 11 and IR 2 was discarded in order to avoid an excess of image artefacts.

Table 3

Relative image noise for each iterative reconstruction level (IR 1-5) compared with the full radiation dose images reconstructed with filtered back projection (FBP) and calculated minimum relative exposure that is needed to obtain image noise levels comparable with the full dose reference when different IR levels are used for image reconstruction instead of FBP.

	FBP	IR1	IR2	IR3	IR4	IR5
Rel. noise	100%	89%	78%	66%	54%	43%
Min rel. exposure	100%	79%	60%	43%	30%	19%

The matching result for the study protocol is printed in bold type.

IR level 2 to obtain comparable image noise levels to the reference protocol. Percentages of calculated tube voltage settings (120/100/80kV) in this reference population were 0/83/17% (TVA 8) and 0/11/89% (TVA 11). Because of the large differences in relative radiation exposure between 100 and 80kV in the TVA grade 11 simulation (79% vs 60%), a TVA grade 8 setting (84% vs 79%) was chosen for the randomized patient trial.

The institutional standard protocol for chest CT, as described above, was used for the reference group (A). Results from the ex ante trials were used to configure the study protocol (B) on the navigator console (TVA grade 8 with 120 ref. kV, TCM with 100 ref. mAs, pitch=0.8, slice acquisition=128 × 0.6 mm, gantry rotation time=0.5 seconds) including the presets for image reconstruction (axial series, slice thickness=5 and 1 mm, increment=5 and 0.7 mm, soft tissue and sharp kernel). The injection protocols for different tube voltages were stored on the user interface of a dual-head power injector capable of dual flow (Stellant CT, Medrad, Volkach, Germany) for time-saving clinical workflow. A diluted mix-bolus was injected for examinations at 100kV (70% iodine: 30% saline) and 80kV (50% iodine: 50% saline), flow and delay were not changed. The scan range was defined from the sixth cervical vertebra to the twelfth rib. Thick slice images (5 mm slice thickness, 5 mm increment) were reconstructed for image evaluation using a soft and a sharp FBP convolution kernel in the reference group (A: B41 and B70, respectively) and a soft and sharp IR convolution kernel in the study group (B: I41 and I70, respectively).

2.3. Image quality

Both objective and subjective image quality were assessed for all 112 patients in a blinded and randomized fashion on a picture archiving and communicating workplace (Syngo Plaza, Siemens Healthineers GmbH, Erlangen, Germany). Image datasets were displayed with a preset soft tissue (width/center=400/50 HU) and lung window (1700/−600). AVs and their SDs were assessed by analyzing regions of interest (ROIs) within the pulmonary trunk, and the aortic root and the dorsal muscles on the right and left side by using soft convolution kernel reconstructions. ROIs were placed manually as large as possible, whereas focal changes in attenuation and artefacts were avoided. Image noise was defined as the SD of attenuation values and signal-to-noise ratio (SNR) as attenuation values divided by its SD. CNR was calculated using equation 1:

$$\text{CNR} = (\text{AV}_{\text{vessel}} - \text{AV}_{\text{muscle}}) / \text{SD}_{\text{vessel}}$$

Subjective image quality was assessed by 2 board-certified radiologists (both with 7 years of experience). Both were blinded to all technical and patient-related data, and evaluated the overall diagnostic image quality, the overall image noise, and the overall image artefacts (1: very poor, not for diagnostic use; 2: poor, only limited diagnostic quality; 3: moderate, acceptable diagnostic quality; 4: good, fully diagnostic quality; 5: very good, best possible image quality) on a 5-point Likert scale.

2.4. Radiation dose

The volumetric CT dose index (CTDI_{vol}) and the dose length product (DLP) were recorded for each patient examination. Effective dose (ED) was estimated by multiplication with the published tube voltage-dependent conversion factors based on Publication 103 of the International Commission on Radiation Protection.^[16]

Table 4

Patient characteristics and exposure parameters.

Group	Study group			Control group
	80kV	100kV	Overall	120kV
n	15	47	62	50
Sex [F/M]	7/8	16/31	23/39	20/30
Age, y	53 ± 23	63 ± 15	61 ± 18	57 ± 15
BMI, kg/m ²	21 ± 4	26 ± 4	25 ± 4	27 ± 6
Ref. mAs	269	130	n.a.	100
Eff. mAs	183 ± 45	126 ± 34	141 ± 45	100 ± 30
CTDI _{vol} , mGy	3.7 ± 0.9	5.0 ± 1.4	4.8 ± 1.5	6.8 ± 2.0
DLP, mGy × cm	124 ± 34	188 ± 55	174 ± 57	248 ± 71
ED, mSv	1.9 ± 0.6	2.7 ± 0.8	2.5 ± 0.8	3.6 ± 1.0
Iodine, g	8.1	11.3	n.a.	16.1

BMI=body mass index, CTDI_{vol}=volumetric computed tomography dose index, DLP=dose length product, ED=effective dose.

2.5. Statistical analysis

Values are given as mean and SD if distributed normally, and as median and range whenever the Gaussian distribution, tested by Kolmogorov-Smirnov tests, could not be assumed. The pretest results were used for sample size calculations based on an equivalence hypothesis for image noise with a statistical power of 80%, considering a 5% significance level and an equivalence limit of 10% (1.6HU image noise).^[17] Student *t* test or nonparametric Mann–Whitney *U* test was used in dependence of data distribution to compare radiation dose, attenuation values, image noise, image contrast, SNR, CNR, and subjective image quality between the study group and the reference group. Subgroup analysis was carried out using nonparametric Kruskal–Wallis analysis of variance and post hoc pair-wise tests. Inter-rater agreement was assessed using Cohen weighted kappa test. Significance levels of 0.05 were assumed. Statistical analysis was performed using the software package PASW Statistics 18.0 (SPSS Inc., Chicago, IL).

3. Results

3.1. Patient characteristics

Minimal sample size to obtain an assumed statistical power of 80% was calculated to be n=49 for each group. In all, 112 consecutive patients were included and randomly assigned to the reference (A: n=50) and the study group (B: n=62). No patient was excluded. All examinations were conducted without hazardous incidents. Patient characteristics and patient exposures are shown in Table 4. The TVA algorithm selected 100kV in 47 examinations and 80kV in 15 examinations. None of the examinations of the study group was performed using a 120 or 140-kV setting. Patients of the study group who were automatically selected for 80kV had a significantly lower BMI (21 ± 4 kg/m²) than those who were selected for 100kV (26 ± 4 kg/m²; *P*=.001). However, no statistical difference was found for the overall BMI in the study group (B) compared with the reference group (A; *P*=.126).

3.2. Iodine dosage

The fixed iodine injection protocol for the reference group (A; 46 mL) had a total iodine content of 16.1g. The mixed 70:30 contrast-saline bolus in the 100-kV subgroup of the study collective correlates with 32 mL contrast media and an iodine

Table 5
Results of objective measurements.

Group	Study group			Control group
	80 kV	100 kV	Overall	120 kV
n	15	47	62	50
Aorta				
AV, HU	203 ± 35	181 ± 33	189 ± 39	160 ± 42
SD	16 ± 2	16 ± 2	16 ± 2	15 ± 2
SNR	13 ± 4	11 ± 3	12 ± 4	11 ± 4
CNR	10 ± 3	8 ± 2	9 ± 3	8 ± 3
Pulmonary trunk				
AV, HU	166 ± 39	176 ± 50	172 ± 48	163 ± 58
SD	16 ± 2	16 ± 2	16 ± 2	16 ± 2
SNR	10 ± 2	11 ± 3	11 ± 3	10 ± 4
CNR	7 ± 3	8 ± 3	7 ± 3	7 ± 4
Muscle				
AV, HU	54 ± 8	48 ± 7	50 ± 7	49 ± 6
SD	16 ± 2	16 ± 2	16 ± 2	15 ± 3

AV=attenuation values, CNR=contrast-to-noise ratio, HU=Hounsfield units, SD=standard deviation representing image noise, SNR=signal-to-noise ratio.

dosage of 11.3 g iodine, and the 50:50 contrast-saline bolus in the 80 kV subgroup with 23 mL and 8.1 g iodine. Hence, the overall iodine dosage was 10.4 g in the study group (B), and the reduction compared with the reference group (A) was 35%.

3.3. Radiation exposure

Radiation dose parameters (CTDI_{vol}, DLP, and ED) were significantly lower in the study group (B) compared with the reference group (A; all *P* < .001, Table 4). Radiation dose reduction was approximately 30% when calculated for the entire study group and further decreased to 47% when calculated separately for the patients examined at 80 kV. The radiation dose reduction in the 100 kV subgroup was 25%.

3.4. Image quality

Objective image quality criteria of the ROI measurements are given in Table 5. Image noise was comparable between the study group and the reference in the aorta and the pulmonary trunk (*P* = .098 and .463). Also, pulmonary attenuation values, contrast, SNR, and CNR, and also aortic SNRs were equivalent between both groups (*P* = .264, .313, .293, .629, and .062). However, significantly higher attenuation values, contrast, and CNR were found in the aorta using the study protocol (all *P* < .01). Pair-wise tests within voltage subgroups only showed significantly higher CNR values for examinations with 80 kV (*P* = .023; Fig. 3). The post hoc calculated 2-tailed statistical power for differences in image noise was 81%, considering an equivalence limit of 10% (1.6HU) and a significance level of 0.05.

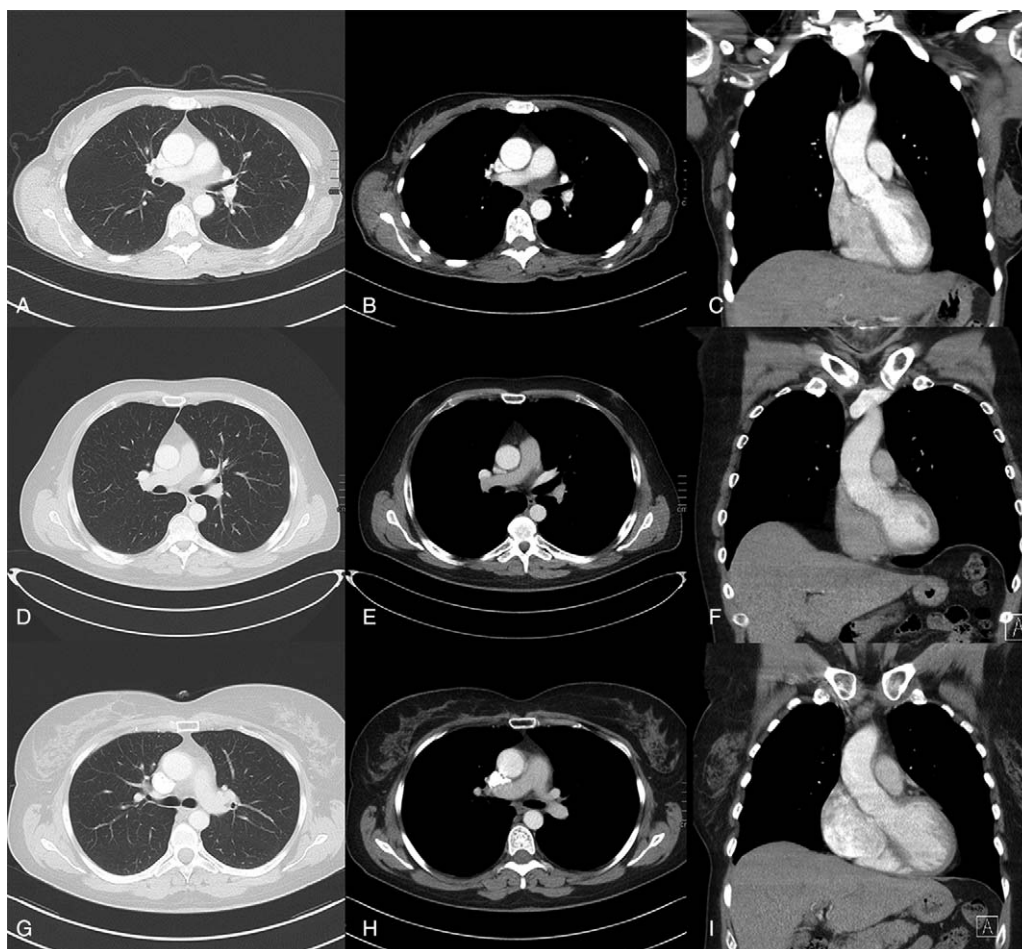


Figure 3. Image quality obtained with 80 kV (A–C), 100 kV (D–F), and 120 kV (G–I). Images are displayed using the same window settings (width/center = 1700/–600 and 380/50).

Table 6
Results of subjective image evaluation.

Likert scale	Study group									Control group		
	80 kV			100 kV			Overall			120 kV		
	15			47			62			50		
n	Quality	Artefacts	Noise	Quality	Artefacts	Noise	Quality	Artefacts	Noise	Quality	Artefacts	Noise
5	1	0	2	10	4	4	11	4	6	8	1	5
4	12	9	13	36	39	36	48	48	49	39	43	35
3	2	6	0	1	4	7	3	10	7	3	6	10
2	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0

Likert scale ratings represent: 1—very poor, not for diagnostic use; 2—poor, only limited diagnostic quality; 3—moderate, acceptable diagnostic quality; 4—good, fully diagnostic quality; 5—very good, best possible image quality.

Subjective image analysis criteria were widely consistent between the study and the control group. The data are presented in Table 6. Interobserver agreement was substantial: the kappa value was 0.73 overall, 0.70 in the study group and 0.78 in the control group. Subjective image quality evaluation was not statistically different between the study and the reference groups for overall diagnostic image quality ($P=.81$), image artefacts ($P=.87$), and image noise ($P=.76$). Nor were the differences in the subgroup analyses significant for overall diagnostic image quality ($P=.17$) and image noise ($P=.92$). However, image artefacts slightly increased in the 80-kV images (mean ranks at 80/100/120 kV: 44/61/56), with increased ratings as “moderate” with acceptable influence on the image quality (score 3) and no rating as “very good” without artefacts (score 5), were statistically significant compared with the 100-kV subgroup (pair-wise post hoc $P=.02$).

4. Discussion

The systematically designed study protocol provided equivalent objective and subjective image quality, despite the substantial reduction in radiation exposure and iodine dosage, each by approximately one-third, when compared with the reference, by combined and individually adapted application of the latest technical developments in contrast-enhanced CT of the chest.

Many articles have recently been published concerning the advantages of low tube voltage examinations of the chest considering increased CNR or decreased radiation doses.^[12,18] Further literature states show that it is feasible to reduce iodine dosage by taking advantage from the increased iodine contrast, whenever the x-ray spectra converge towards the k-edge of iodine (33.2 keV), for several indications.^[19–21] In the chest, Szucs-Farkas et al^[22] found comparable image quality for patients with pulmonary embolisms, and reduction of the iodine load by 37% and the radiation dose by 57%, if the tube voltage was reduced from 120 to 80 kV. Zhang et al^[23] found increased image quality for a coronary CT angiography protocol, with iodine reduced by 52% and radiation dose by 56% using a combination of tube voltage reduction from 100 to 80 kV and different IR algorithms in rather high-dose protocol (5.5 and 2.4 mSv). However, none of these studies was performed following an equivalence hypothesis. This study provides a systematic approach to find the highest extent of iodine dosage and radiation dose reduction that is suitable for each individual patient by automated TVA, TCM, and IR. The extent of both reductions of the iodine dosage (35%) and the radiation dose (31%) lies within the overall range of previously published studies. Moreover, this study provides detailed insight into the gradual effects of different settings of the

current technical developments and their synergetic interaction on 1 side, and on the other, provides examples of judicious combinations for a clinical routine collective.

However, there are some limitations of this study that need to be addressed. First, despite the lowest radiation dose in the 80-kV subgroup, the objective image quality for the aortic measurements was superior compared with both the reference collective and the 100-kV subgroups. Hence, a further decrease of the iodine dosage and radiation dose might have been possible in these patients. Second, we intentionally did not evaluate the second protocol given by the ex-ante trials (TVA grade 11, IR-level 2) to prevent a further divergence between the subgroups and avoid conflicts with the tube capacities, because insufficient tube current modulation is a well-known limitation for low tube voltage examinations. The increased image artefacts in the 80-kV subgroup confirmed this decision. Nevertheless, this might be a suitable approach to further exploit the advantages of low tube voltages. Moreover, the latest x-ray tubes have increased outputs and allow for narrow adjustment of the tube voltage in steps by only 10 kV and down to 70 kV. Thus, more aggressive settings of TVA and higher IR levels are promising and should be evaluated for future scanner generations. Third, for this proof of concept, we did not yet evaluate a certain population or certain indications and therefore did not evaluate diagnostic accuracy. Fourth, our findings provide information about chest CT in a late aortopulmonary contrast setting without individual identification of the circulation time. Transfer of these findings to angiographic procedures or soft tissue imaging has to be confirmed by further studies. Fifth, we used a dilution of the contrast media bolus in order to keep the total volume and therewith bolus dynamic unchanged. Our results cannot be transferred to injectors that are incapable for dual flow setting.

5. Conclusions

In conclusion, we demonstrated that the average iodine dosage, and also the average radiation exposure in patients undergoing contrast-enhanced CT of the chest can be reduced by one-third if individual TVA, TCM, and IR are judiciously combined in a structured examination protocol to provide a consistent image quality in a clinical routine setting.

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