Automated Computed Tomography Dose-Saving Algorithm to Protect Radiosensitive Tissues

Estimation of Radiation Exposure and Image Quality Considerations

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Purpose: To evaluate radiation exposure and image quality in thoracic computed tomography (CT) using a new dose-saving algorithm to protect radiosensitive organs.

Materials and Methods: For dose measurements, an Alderson RANDO phantom equipped with thermoluminescent dosimeters was used. The effective dose was calculated according to the International Commission on Radiologic Protection 103. Exposure was performed on a second-generation dual-source CT. The following parameters for thoracic CT were used: 160 effective mAs, 120 kV, scan range of 30 cm, collimation of 128 × 0.6 mm. For the acquisition, the tube current modulation type XCare was used, which reduces the tube current for anterior tube position to minimize direct exposure to anterior located organs. To compare differences, scans with and without XCare were performed. Objective signal-to-noise measurements were evaluated, and the subjective noise perception was rated in a 3-point scale (1: excellent, 3: affecting diagnostic accuracy) in 30 patients with a standard thoracic examination and a follow-up using XCare.

Results: A substantial dose reduction in radiosensitive tissues was evident using the dose-saving algorithm XCare. Specifically, reductions of 35.2% for the female breast and 20.1% for the thyroid gland were measured, resulting in a decreasing effective whole-body dose of 8.0% and 14.3% for males and females, respectively. The objective and subjective evaluation of image quality showed no significant differences between both scan protocols ($P > 0.05$). Mean signal-to-noise ratio was 1.3 ± 0.2 and 1.2 ± 0.2 in scan protocols without and with XCare, respectively. The subjective scores at the level of the pulmonary trunk were 1.2 ± 0.4 and 1.4 ± 0.5 in standard chest scan and scans with the dose-saving algorithm XCare, respectively.

Conclusions: The XCare technique protects radiosensitive organs like the female breast and the thyroid gland without affecting image quality. Therefore, this dose-saving algorithm may be used in thoracic CT examinations in male and female patients.

Key Words: XCare, female breast, Alderson RANDO phantom, dose-saving technique, effective dose

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The continuously evolving field of computed tomography (CT) in the noninvasive diagnostic workup of numerous diseases has led to a substantial increasing number of CT examinations in various organ regions.[1] As a matter of course, the benefit of every CT examination has to be weighed against the potential risks of cancer induction. Although there is a small individual risk, the radiation exposure in an increasingly large population may create a public health issue in the future.[2–4] Although many clinicians may still be unfamiliar with the magnitude of radiation exposure of CT examinations, the radiologist has to be aware of the latest dose-saving strategies to keep the radiation exposure as low as reasonably achievable in daily routine.[5]

Several dose-saving strategies have been introduced and integrated in routine clinical workflow, such as automated exposure control, automated attenuation-based tube potential selection, high-pitch spiral CT, iterative reconstructions, or adaptive dose shields to avoid the z-overscanning.[6–12]

In second-generation dual-source CT, a new dose-saving technique was introduced to limit the exposure of radiation-sensitive organs. This is especially true for female breast tissue, which recently was found to be more radiosensitive than previously assumed, reflected in an increased tissue weighting factor in the recent recommendation of the International Commission on Radiologic Protection.[13] When XCare technique is used for data acquisition, the tube current is reduced for tube position where x-rays pass the patient from anterior to posterior. By doing so, direct exposure of radiation-sensitive organs is reduced. However, to be able to maintain image quality, the tube current is increased for the remaining projections (posterior to anterior) to end up with the same milliamperes per rotation.

Although several other dose-saving algorithms can be directly evaluated by monitoring the volume CT dose index ($CTDI_{Vol}$) and the dose-length product (DLP), the XCare algorithm does not affect these parameters due to a mere angular beam modulation, whereas total tube current and tube voltage remain constant.

The aim of the study was an experimental estimation of organ equivalent dose and effective dose and to evaluate the influence of the above-mentioned XCare dose-saving algorithm with respect to image quality. To the author's knowledge, it is the first evaluation of this recently introduced dose-saving technique.

MATERIALS AND METHODS

Dosimetry

Experimental dose measurements were performed using an anthropomorphic, hermaphrodite male phantom with breast phantom attachments (Alderson RANDO phantom, Alderson Research Laboratories Inc., Stanford, CT). To perform exposure measurements, the phantom was equipped with 117 thermoluminescent dosimeters (TLDs) with dimension of 1 × 1 × 6 mm (TLD-100H,

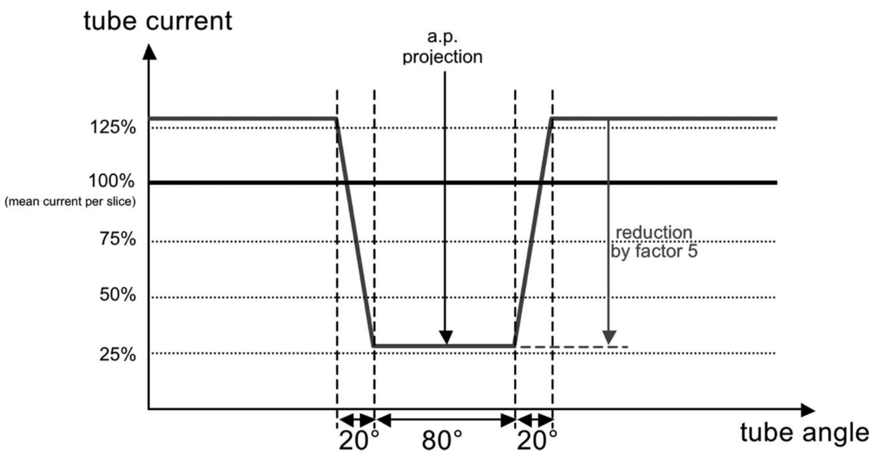

FIGURE 1. The XCare technique reduces the tube current for the tube position where x-rays pass the patient from anterior to posterior.

Bicon-Harshow, Radiation Measurement Products, Cleveland, OH) according to previously published dose measurement studies.[1,14,15]

One hundred seventeen TLDs in 39 different positions in the Alderson RANDO phantom were used to assess the organ doses dependent on the anatomic position of each organ. Due to measurement deviation, 3 TLDs were placed at each point of dose measurement to minimize bias. The numbers of TLDs allocated to different organ position were as follows: 3 at the brain, thyroid gland, esophagus, thymus, heart, breast, stomach, upper colon, spleen, kidneys, adrenal glands, pancreas, small intestine, lower colon, urinary bladder, muscle tissue, red bone marrow, skin, ovaries, and testicles; 42 at the lung; and 15 at the liver.

The evaluation of the irradiated TLDs was performed using a TLD reader (Model 5500 TLD Reader, Bicron Radiation Measurement Products, Solon, OH) within 24 hours after radiation exposure. The readout TLD values in nanocoulombs were multiplied by an individual calibration factor, which was defined by means of parallel exposure of 33 TLDs with a known radiation dose using 102 kV and 10 mAs for 34 milliseconds at an SSD of 100 cm (Philips Optimus 65, Philips Medical Systems, PC Best, The Netherlands). To minimize the Heel effect, wire markers in the field were avoided, and all expositions were done in the same position with respect to the orientation of the x-ray tube. Crosschecked by an ionization dosimeter positioned in the same phantom depth, the reference TLDs were exposed with a dose of 1.081 mGy. No further correction factors were used as the calibration voltage is close to the CT's tube voltage.

The effective dose was calculated by summarizing the weighted organ doses according to the guidelines of the International Commission on Radiologic Protection 103.[13] A radiation dose of simulated small organs (ie, thyroid gland) was directly rated into the calculation. Doses of larger organs (ie, lung) were determined by assessing the mean of measured TLDs from the entire organ.

To assess sex-specific differences, the testicles were used to measure the male-specific effective dose, whereas radiation dose of the breast and the ovaries was used to account for the female-specific radiation exposure.

Experimental Scan Protocols

Exposure was performed on a second-generation 128-slice dual-source CT system (SOMATOM Definition Flash, Siemens Medical Solutions, Forchheim, Germany). Thorax scans were performed with following parameters: 160 effective mAs without automated exposure control, 120 kV, collimation of $64 \times 2 \times 0.6$ mm with z-flying focal spot, scan range of 30 cm, pitch of 0.75, and 330 milliseconds of gantry rotation time.

Scans in the experimental setup were performed without automated exposure control to evaluate only the influence of the dose-saving technique XCare. In clinical routine, the automated exposure control is routinely performed and tends to a further dose reduction.

The dose-saving technique XCare (Siemens Medical Solutions, Forchheim, Germany) reduces dose to radiation-sensitive organs by reducing the tube current to up to 20% for the anterior 120 degrees of projection and increasing the tube current in the remaining projections, respectively (Fig. 1). Thus, the tube current is reduced for tube position, where x-rays pass the patient from anterior to posterior, to reduce the direct exposure of radiosensitive organs. To maintain image quality, the tube current is increased for the remaining projections (posterior to anterior) to get the same milliamperes per rotation. Choosing this full-automated algorithm, the whole scan range is exposed in the described manner.

To evaluate the influence of XCare, a thorax scan with XCare and a second scan without this dose-saving algorithm were performed. The $CTDI_{Vol}$ and DLP were noted.

Objective Assessment of Image Quality

For objective measurements, the Alderson RANDO phantom was scanned a second time with and without XCare adding sodium chloride depots (anterior, posterior, right, left sided) directly outside the phantom at the level of the female breast (Fig. 2). Images were reconstructed in a medium B31f kernel and a slice thickness of 3 mm. In a standard window setting of 50 HU/350 HU, regions of interest were placed into the sodium chloride depots with a size of 20 mm^2. Signal-to-noise ratio is defined as the ratio between a signal and the background noise.

Patient Population for Subjective Assessment of Image Quality

The dose-saving algorithm XCare was routinely applied in female patients since September 2010 on the above-mentioned second-generation dual-source CT system.

Thirty consecutive female patients (mean age, 68.9 ± 14.2 years; range, 35–86 years) in whom a contrast-enhanced examination of the thorax had been performed and who had a previous contrast-enhanced thorax CT on our first-generation 64-slice dual-source CT (SOMATOM Definition, Siemens Medical Solutions, Forchheim, Germany) without XCare were retrospectively included in the present study. Both CTs had been performed due to oncologic staging purposes. Exclusion criteria were scan parameters other than

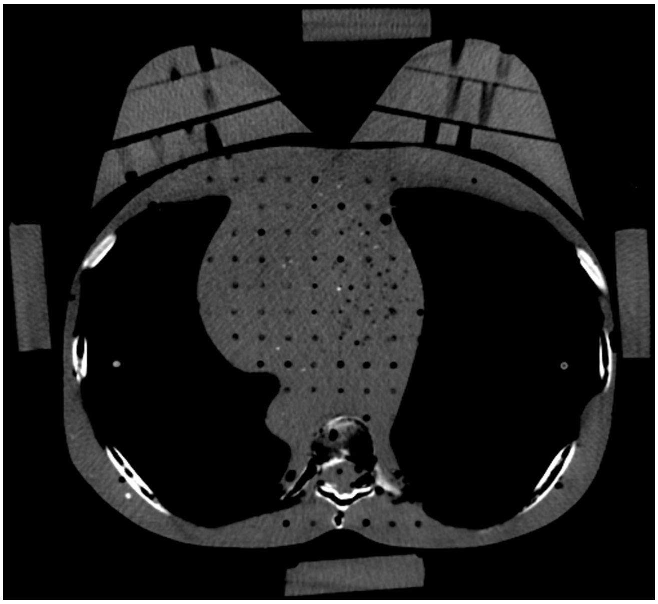

FIGURE 2. Slice for the noise measurement with 4 sodium chloride depots to evaluate differences between the 2 scan protocols (with and without XCare).

160 effective mAs with automated exposure control, 120 kV, slice thickness of 3 mm, B31f kernel. An agreement of the local institutional ethics board for research was not necessary because of the retrospective study design.

Subjective Image Quality

Image data were transferred to a Multi-Modality Workplace (Siemens Medical Solutions) and anonymized. Two radiologists with more than 4 years (D.K.) and 10 years (M.H.) of experience in thoracic imaging performed the image quality assessment. The radiologists rated their visual perception of noise in all data sets ($n = 30$ scans without XCare, $n = 30$ scans with XCare) in an axial slice at the level of the origin of the supra-aortic vessels, the pulmonary trunk, and the medial lobe. The information on which scan was performed with the dose-saving algorithm was blinded. The radiologists used in each data set a soft-tissue (50 HU/350 HU) and lung window (650 HU/1500 HU) setting for decision making. The image noise was rated as minimal (score 1, excellent image quality), moderate (score 2, good image quality without affecting diagnostic accuracy), or severe (score 3, poor image quality affecting the diagnostic accuracy).

Statistical Analysis

Results of the radiation dose measurements were expressed as mean and differences in percentages. Results of the image quality analysis were expressed as mean and standard deviation. Differences of noise measurements between the 2 groups were evaluated with the paired Student t test. Differences between the ratings of the image noise in the individual groups were assessed using a Wilcoxon signed-rank test. A P value <0.05 was considered to be significant. Interobserver agreement between the 2 readers was evaluated with the [Kappa] statistic. Agreement was considered as moderate to fair if values were less than 61%, substantial if values were greater than 61%, and high if values were greater than 81%. The statistical analyses were performed using SAS software (SAS Institute Inc., Cary, NC).

TABLE 1. Effective Doses of Standard Thoracic CT Examination (1) and Thoracic CT Using the Dose-Saving Technique XCare (2)

Protocol	Effective Dose Male (mSv)	Effective Dose Female (mSv)	Total mAs	$CTDI_{Vol}$ (mGy)	DLP (mGy cm)
(1) Standard	6.1	7.9	1657	10.7	348
(2) XCare	5.6	6.8	1599	10.8	342

$CTDI_{Vol}$ indicates volume CT dose index; DLP, dose-length product.

TABLE 2. Measured Organ Equivalent Doses of Both Scan Protocols (mSv)

Organ/Tissue	(1) Standard	*(2) XCare*
Thyroid gland	0.72	*0.58*
Esophagus	0.00	*0.00*
Lung	1.98	*2.02*
Breast	1.82	*1.18*
Stomach	1.36	*1.24*
Liver	0.57	*0.46*
Colon	0.07	*0.06*
Urinary bladder	0.01	*0.01*
Red bone marrow	0.19	*0.21*
Skeleton	0.01	*0.02*
Skin	0.01	*0.01*
Male gonads	0.01	*0.00*
Female gonads	0.02	*0.02*
Remaining organs	*1.17*	0.99

RESULTS

Radiation Dose

The CTDI, DLP, and the estimated effective dose are shown in Table 1. Although CTDI and DLP showed similar values in both scan protocols, the effective whole-body dose showed a dose reduction of 8.0% and 14.3% using the dose-saving algorithm XCare for males and females, respectively. This is caused by a substantial dose reduction in radiosensitive tissues of 35.2% at the female breast and 20.1% at the thyroid gland. Details about organ equivalent doses are displayed in Table 2. Protocol-related differences in organ equivalent doses are illustrated in Figure 3 for selected organs. Due to the breast tissue in the primary scan range, females received an increased effective dose of 30.0% and 21.0% in a thorax CT scan without and with the dose-saving algorithm XCare, respectively.

Image Quality

The objective noise measurements are displayed in Table 3. Mean signal-to-noise ratio was 1.3 ± 0.2 and 1.2 ± 0.2 in scan protocols without and with XCare, respectively ($P > 0.05$). The subjective ratio of noise perception also showed no significant differences between both scan protocols ($P > 0.6$). The subjective score was 1.2 ± 0.4 and 1.3 ± 0.5 at the level of the origin of the supra-aortal vessels, 1.2 ± 0.4 and 1.4 ± 0.5 at the level of the pulmonary trunk, and 1.3 ± 0.4 and 1.4 ± 0.5 at the level of the medial lobe in standard chest scan without and with the dose-saving algorithm XCare, respectively. The interobserver agreement was high, with κ values of 0.86 and 0.83 in evaluated scans without and with the dose-saving technique XCare, respectively.

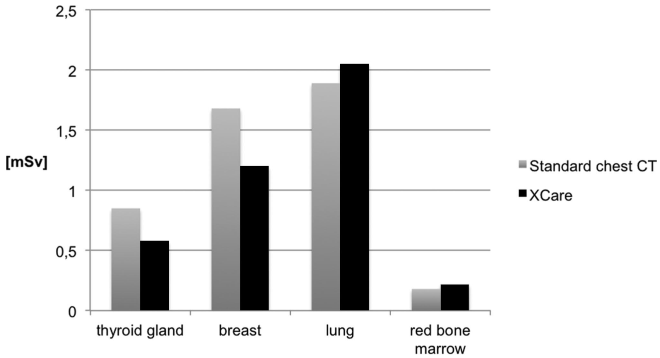

FIGURE 3. Exemplary organ equivalent doses and the influence of both scan protocols. Using XCare, the organ equivalent doses of the radiosensitive thyroid gland and the female breast decrease, whereas the radiation exposure of the lung and the red bone marrow increases due to the added exposure in the dorsal body parts.

TABLE 3. Measured SNR Ratio in the Sodium Chloride Depots Outside the Phantom (Mentioned Also in Fig. 1) of the Standard Thoracic CT and the CT Scan Using XCare

	Standard Scan	Scan With XCare
Ventral	1.12	0.95
Dorsal	1.29	1.32
Right	1.59	1.32
Left	1.24	1.07

DISCUSSION

The increasing number of diagnosed breast cancer cases is a cause of concern. A number of studies evaluated the influence of medical radiation exposure on future occurrence of malignant tumors in women who were exposed to high radiation doses due to multiple fluoroscopic examinations or treatment by radiotherapy.[16–18] In CT examinations of the thorax, the breast is always in the scan range, but is rarely an organ of interest. With consideration of the extremely radiosensitive glandular tissue in the female breast, dose-saving algorithms have to be applied, if possible.[14–16]

Several dose-saving methods such as bismuth shielding or automated tube current modulation techniques have been evaluated and introduced in clinical routine.[16,19–22]Although automated algorithms, for example, automated tube current modulation, are widely accepted and integrated in clinical workflow, several shielding methods are associated with time-consuming patient preparation and may be implemented only in a selected patient population, for example, younger women. These dose-saving techniques have the potential for significant dose reduction up to 25% in attenuation-based tube potential selection or up to 15% with automated exposure control.[6,9]

The recently introduced automated XCare algorithm may achieve a decreasing organ equivalent dose of the female breast by an angular beam modulation with reduced direct radiation in the anterior 120 degrees of projection. The radiation exposure was decreased not only by 35% in the female breast but also by 20% in the thyroid gland, which resulted in a lowering of the effective whole-body dose by about 8% to 14% in males and females. The analysis of image quality and subjective noise perception showed no significant difference between the standard examination and examinations using the XCare dose-saving algorithm.

Although the radiation exposure is relatively low outside the scan range, the tissues irradiated by the primary beam received substantial organ equivalent doses. In examinations of the thorax, this results in an increased effective dose of females compared with males, in the present study of 21.0% to 30.0%.

An effect of the XCare angular beam modulation is a decrease in organ equivalent doses in the anterior body parts and an increase of radiation exposure in the dorsal body parts, resulting in a reduction of radiation exposure of radiosensitive organs, for example, the female breast and the thyroid gland, and a slightly increasing exposure of the lung, the skeleton, and the red bone marrow.

To maintain the noise level of the scan without XCare, in the case of scan with XCARE, on one hand, the total tube current per rotation is maintained by increasing the tube current slightly for posterior projections to compensate for the milliamperes decrease for posterior projections. On the other hand, a dedicated reconstruction technique is used, which considers the amount to dose of each projection by applying a dose-dependent weight for the rays during the reconstruction process.

This fact demonstrates further possible applications, for example, in head and neck imaging to protect radiosensitive tissues like the thyroid gland or the ocular lens, which, however, has to be addressed in further studies. Furthermore, the possible benefit in imaging of children by decreasing radiation exposure in sensitive organs should be mentioned.

A possible limitation of this study is the use of a hermaphrodite phantom for dose measurements. Although absolute organ equivalent doses and whole-body effective dose may vary depending on breast size, shape, and patient size, this does not affect the analysis of relative dose-saving potential and the relation of dose values for the different scan protocols. Furthermore, these differences in body size between phantoms and real patients and differences in composition and density of phantom materials and real tissues could only be included in a Monte Carlo simulation using tomographic phantoms.[23]

In conclusion, the XCare technique is a simple, widely applicable technique to protect radiosensitive organs like the female breast and the thyroid gland without significantly affecting the image quality. Therefore, this dose-saving algorithm should be used in thoracic CT examinations in male and female patients with a possible decrease in organ equivalent doses of sensitive organs by about 30%. Further possible applications in head and neck imaging and children should be evaluated.

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