Organ-Specific vs. Patient Risk-Specific Tube Current Modulation in Thorax CT Scans Covering the Female Breast

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ABSTRACT

An important goal in modern CT imaging is reducing the dose delivered to patients especially to risk-relevant organs. This work compares the clinically applied dose reduction techniques mAs-minimizing tube current modulation (mAsTCM) and a typical organ-specific TCM (osTCM, here: X-Care, Siemens Healthcare) with a novel radiation risk-minimizing tube current modulation (riskTCM) with a focus on the dose delivered to the female breast. The mAsTCM minimizes the mAs product as a surrogate parameter for the patient dose but does not consider the different organs' risks. In contrast, osTCM aims to minimize the dose delivered to the female breast by reducing the tube current for anterior projections. The riskTCM minimizes the patient risk by minimizing the effective dose to the patient, which is done by taking accounting for the organ doses. In this study, the dose reduction effect of the TCM techniques is compared by simulations based on clinical CT scans. Thereby, riskTCM reduces the effective dose by up to 35% in comparison to mAsTCM, and by up to 30% in comparison to osTCM depending on the anatomical region and the patient.

Keywords: CT, dose reduction, tube current modulation, chest imaging.

1. INTRODUCTION

Since the invention of the first CT scanner, the scanners improved greatly and the amount of performed scans increased from 3 million in the early 1980s to 67 million in 2006.[1] As ionizing radiation is used for CT scans and it is well known that ionizing radiation involves the risk of damaging the DNA, which can cause cancer, it is critical to reduce the patient's risk by decreasing the dose delivered to the patient but maintaining image quality on the other hand. In modern CT imaging, there are several dose-saving methods, for instance, automatic exposure control (AEC),[2] automated tube potential selection,[3] and adaptive dose shields.[4] This study is focused on the tube current modulation part of AEC that varies the tube current during gantry rotation and along the z-direction.[5]

A commonly used tube current modulation (TCM) technique is the mAs-minimizing TCM (mAsTCM) that minimizes the mAs product and reaches an mAs reduction of $20 - 40\%$ for the scanned body depending on the region that is investigated.[6,7] The mAs is used as a surrogate value for the patient's dose in this method. An issue with the mAsTCM is that it is based on a physical quantity and does not consider the radiation sensitivity of different organs. The influence of ionizing radiation on the human body, and therefore the risk to induce cancer, is well known. The international commission on radiological protection (ICRP) provides a guideline of protection for people against the effects of radiation exposure and created weighting factors that represent the risk

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of radiation to induce cancer for single organs.[8] These weighting factors allow for calculating the effective dose that can be chosen as a stochastic parameter of the patient's risk.[9] Since 2007, the radiation sensitivity of the female breast is stated in the ICRP Publication of 2007[8] to be higher than expected. Therefore, several vendors implemented organ-specific tube current modulation techniques to allow to reduce the exposure at certain organs. Here, we are interested in minimizing the dose to the breast and thus osTCM here refers to a reduction of the tube current in the anterior position. Our implementation of osTCM mimics the X-Care algorithm by Siemens Healthcare. It reduces the tube current for the anterior projections (120° in front of the patient) and increases it for the remaining projections, as specified in the literature.[10] Today's osTCM implementations only account for the exposure to a specific organ and do not consider every organs' risks. The radiation-risk minimizing TCM (riskTCM), in contrast, that is detailed in the literature[11] and that was proposed in previous publications[12–14] , minimizes the effective dose by considering all dose-sensitive organs in its cost function.

This work aims at evaluating the dose reduction achievable with riskTCM in comparison to mAsTCM and osTCM. A special focus is laid on the evaluation of the dose delivered to the female breast as this is the organ accounted for by osTCM in thorax CT scans.

2. MATERIAL AND METHODS

2.1 Dose per view estimations

To calculate the tube current modulation curves and the resulting changed effective doses, the effective dose before TCM needs to be estimated for each view and organ. For this, a previous CT reconstruction is necessary. Since this study is a simulation study, CT reconstructions are already provided. In practice, an approach to receive an estimated CT scan of a patient is to use a deep-learning model which performs a reconstruction using the available topograms.[15] The dose is calculated from the existing CT reconstructions by using the deep dose estimation (DDE) algorithm that is detailed in the literature[16] and was first proposed in a previous publication.[17] DDE reproduces 3D Monte Carlo dose simulations with a two-channel input from a CT reconstruction and a first-order dose estimation. With the calculated dose distribution the effective dose can be calculated by weighting the dose with the organ-specific factor that is defined by the ICRP[8] and sum the weighted dose over all organs:

$$D_{\mathrm{eff}}(\alpha) = \sum_{\mathrm{T}} \int d^3r \, w_{\mathrm{T}}(r) D(\alpha, r). \tag{1}$$

The normalized organ-specific weighting factors w_{T} are listed in Table 1. Equation (1) is the effective dose normalized to a constant tube current. Hence, this effective dose needs to be weighted by the tube current curve and integrated over all views:

Table 1: Tissue weighting factors according to the literature.[8]

Tissue	w_{T}	$\sum w_{\mathrm{T}}$
Bone-marrow (red), colon, lung, stomach, breast, remainder tissues	0.12	0.72
Gonads	0.08	0.08
Bladder, oesophagus, liver, thyroid gland	0.04	0.16
Bone surface, brain, salivary glands, skin	0.01	0.04
	Total	1.00

$$D_{\mathrm{eff}} = \int d\alpha \, I(\alpha) D_{\mathrm{eff}}(\alpha). \tag{2}$$

2.2 Prerequisites

For the simulation study, polychromatic attenuation values are assumed, yielding a projection value of

$$q(L) = -\ln \int dE \, w(E) e^{-\int dL \, \mu(r,E)} \tag{3}$$

$$= -\ln \int dE \, w(E) e^{-p(L)\psi(E)}. \tag{4}$$

This dependency can be written as $q = Q(p)$ and can be inverted by $p = P(q)$, with $P(q)$ as water precorrection function. In order to calculate the noise of an CT image, a Poisson distribute signal before water precorrection and log is considered. Therefore, the variance and thus also the noise of the signal is proportional to

$$Ie^{-q}. \tag{5}$$

This results in a variance of:

$$\mathrm{Var}\, q \propto \frac{e^q}{I}. \tag{6}$$

The variance of the projection value can now be calculated by propagating the error through the water precorrection function as

$$\mathrm{Var}\, p \propto \frac{e(p)}{I} \tag{7}$$

with $e(p)$ as polychromatic exponential function which reduces to a simple exponential function for monochromatic scans.
In order to simulate the TCMs, two surrogates are needed. First, the average of the projection value over all detector rows is calculated:

$$p(\alpha, \beta) = \frac{1}{B}\int_{-B/2}^{B/2} db\, p(\alpha, \beta, b) \tag{8}$$

In this case, $B = 64 \times 0.6$ mm which is a collimation of about 40 mm.
The second surrogate is the 90th percentile of $p(\alpha, \beta)$:

$$p(\alpha) = p_{90\%}(\alpha, \beta). \tag{9}$$

2.3 TCM Approaches

2.3.1 Minimizing the Tube Current Time Product

The mAs-minimizing TCM takes into account that for non-circular regions, for instance, pelvis or shoulders, the attenuation varies for lateral and anterior/posterior views.[6,7] To calculate the optimal tube current for minimizing the mAs product, a central ray approximation is considered that uses the projection data $p(\alpha)$ and interprets this value as central ray value ($\beta = 0$) which is backprojected into the isocenter of the scanner. The mAs minimization can be formulated as cost function

$$C = \int d\alpha \left(\frac{e(p(\alpha))}{I(\alpha)} + \lambda(I(\alpha) - \mathrm{const}) \right), \tag{10}$$

which allows to either keep the noise constant and minimizes the mAs product or to keep the mAs product constant and minimizes noise.

2.3.2 organ–specific TCM

Here, osTCM mimics the X-Care algorithm.[10] It is an organ-specific tube current modulation such that especially the female breast can be prevented from high exposure. The algorithm also reduces the dose exposed to the thyroid gland and eyes but here we focus on the breast. To protect the female breast from radiation exposure the tube current is reduced for anterior projections and for posterior projections it is increased to achieve the same image quality. The anterior projections are defined as the projections within an angle of 120° in front of the patient and the posterior within an angle of 240° on the back of the patient. It should be noted that osTCM is applied for the complete scan even if it covers more regions than just the breast.

2.3.3 Risk-minimizing TCM averaging case

Equation (10) can be modified by considering that the effective dose is also dependent on the projection angle α:

$$C = \int d\alpha (\mathrm{Var}\, p(\alpha) + \lambda (I(\alpha) D_{\mathrm{eff}}(\alpha))). \tag{11}$$

This function can also be minimized by differentiating and yields

$$I^2_{\mathrm{riskTCMavg}}(\alpha) \propto \frac{e(p(\alpha))}{D_{\mathrm{eff}}(\alpha)}. \tag{12}$$

This TCM is called riskTCMavg because it minimizes the effective dose but performs an averaging of the projection values for complementary ray directions.

2.3.4 Risk-minimizing TCM optimal case

In the optimal risk-minimizing TCM the difference of the effective dose of two complementary rays is considered. Consequently, the variance can be received by statistical optimal weighting for example the inverse-variance weighting:

$$V_{\mathrm{opt}}(r) \propto \frac{1}{I + I_{\mathrm{c}}} \tag{13}$$

with I_{c} as complementary tube current. This distinction of complementary rays leads to major changes in the cost function because it is no longer possible to use the central ray approximation. An assumption that can be done in this case is neglecting the cone-beam nature of the beam and just assuming a fan beam geometry because the cone angle is much smaller than the fan beam angle. The image noise can be described by summation over the square-root of all variances:

$$N_{\mathrm{opt}}(I) = \int dxdy\, w(r) \sqrt{\int d\vartheta \frac{e(p(\alpha(\vartheta, r), \beta(\vartheta, r)))}{I(\alpha(\vartheta, r)) + I(\alpha_{\mathrm{c}}(\vartheta, r))}}. \tag{14}$$

The optimization problem can now be formulated as

$$I = \arg\min N_{\mathrm{opt}}(I) \tag{15}$$

with

$$\int d\alpha\, D_{\mathrm{eff}}(\alpha) I(\alpha) = const. \tag{16}$$

The constant can be chosen such that either the effective dose is constant or the image noise. As there is no analytical solution to this optimization problem, the solution has to be found numerically. Details are provided in the literature.[11]

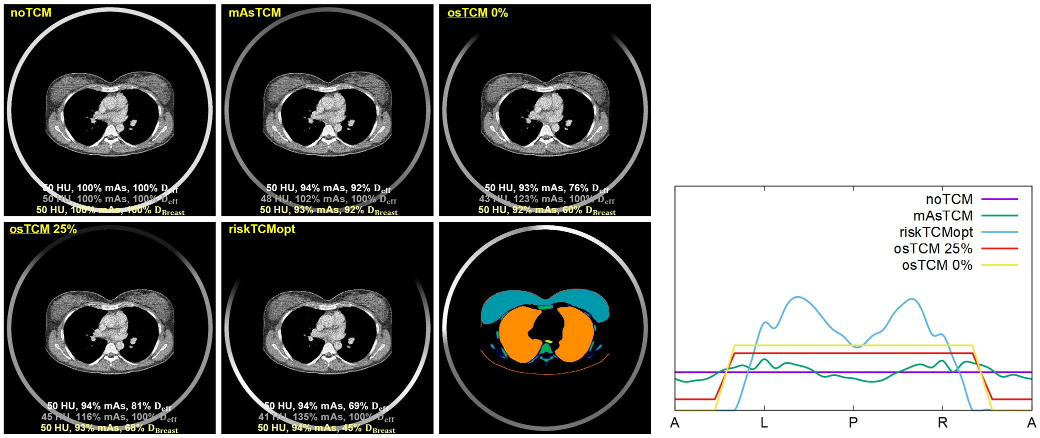
2.4 Materials

For the evaluation the reconstructed volumes of seven CT scans are used. For the simulation of the rawdata the geometry of a Somatom Definition Flash CT scanner with a collimation of $B = 64 \times 0.6$ mm is assumed. These CT images are forward projected with a 2D fan-beam forward projection to obtain rawdata. To reduce the noise in these rawdata a boxcar filter of 15 mm width was applied to the forward projected rawdata. Now, the rawdata can be regarded as being (almost) noise-free and we can add noise corresponding to the desired TCM curves. These noisy rawdata are then reconstructed by FBP. The tube current curves were scaled in a way to either obtain the same image noise for all TCM algorithms, or to obtain the same D_{eff} for all TCM approaches. This allows for an easy comparison of either the resulting effective dose values or the resulting image noise values.

In the following, four tube current modulations are simulated: mAsTCM, riskTCMopt, osTCM with a low value of 25% and osTCM with a low value of 0%. The resulting effective dose values are compared to a scan with constant tube current which is called noTCM.

3. RESULTS AND DISCUSSION

The TCMs can be evaluated for different anatomical regions, e.g. thorax, abdomen and pelvis. In Figure 1, the region of the breast is shown with an image noise of 50 HU.



(a) (b)

Figure 1: a: noTCM, mAsTCM, osTCM 0%, osTCM 25% and riskTCMopt images with $C = 25$ HU and $W = 400$ HU with an additional segmentation image. The circular density plot is the TCM curve for the first five images and it is the effective dose $D_{\mathrm{eff}}(\alpha)$ for the last image. b: TCM curves $I(\alpha)$ as a function of angular position. The letters under the abscissa indicate the anterior, left, posterior and right tube position.

Table 2: Effective doses for different anatomical regions and patients of different tube current modulations. The effective doses are calculated relative to the effective dose with constant tube current. The image quality is kept constant.

Region	Pat.	noTCM	mAsTCM	osTCM (25%)	riskTCMopt
Thorax	1	100%	76%	70%	51%
	2	100%	89%	86%	71%
	3	100%	86%	86%	70%
	4	100%	87%	79%	65%
	5	100%	89%	88%	71%
	6	100%	90%	84%	73%
	7	100%	87%	79%	66%
	Avg	100%	$(86 \pm 5)\%$	$(82 \pm 6)\%$	$(67 \pm 7)\%$
Abd	1	100%	79%	78%	62%
	2	100%	98%	98%	88%
	3	100%	93%	91%	78%
	4	100%	87%	84%	65%
	5	100%	97%	90%	73%
	6	100%	98%	94%	63%
	7	100%	91%	84%	63%
	Avg	100%	$(92 \pm 7)\%$	$(88 \pm 6)\%$	$(70 \pm 10)\%$
Pelvis	1	100%	75%	88%	70%
	4	100%	74%	77%	60%
	7	100%	72%	82%	64%
	Avg	100%	$(74 \pm 2)\%$	$(82 \pm 6)\%$	$(65 \pm 5)\%$

The mAsTCM reduces the effective dose by 8%, riskTCMopt by 31%, osTCM (0%) by 24%, and osTCM (25%) by 19%. This region is circular shaped so mAsTCM results in a mainly constant tube current. osTCM just accounts for the radiation sensitivity of the breast and therefore reduces the tube current for anterior projections and increases it for the remaining projections. The riskTCMopt method reduces the tube current for anterior projections more than for posterior projections because of the risk of the breast. Furthermore, the organ dose to the breast is calculated (highlighted in yellow). For mAsTCM the dose reduction of the breast is 8%, for riskTCMopt 55%, for osTCM (0%) 40%, and for osTCM (25%) 32%. The dose reduction for riskTCMopt is higher than for osTCM because RiskTCMopt minimizes a cost function with detailed anatomical knowledge and on the other hand osTCM assumes the anterior region of the patient independently of the patient's anatomy as 120° in front of the patient.

The results for all regions (Thorax, Abdomen, Pelvis) and patients are shown in table 2. For the evaluation only osTCM with 25% as a low tube current value is shown since this case is the conventional one. The whole body effective doses are calculated supplementary and listed in table 3.

In the final analysis, also the dose of the breast is calculated and listed in table 4. In comparison to noTCM, mAsTCM reduces the effective dose around 2% to 20%, riskTCMopt around 35% to 65%, and osTCM (25%) around 12% to 39%.

Table 3: Whole body effective doses with TCMs.

Pat.	noTCM	mAsTCM	osTCM (25%)	riskTCMopt
1	100%	78%	78%	62%
2	100%	91%	89%	74%
3	100%	88%	88%	74%
4	100%	85%	81%	64%
5	100%	92%	91%	77%
6	100%	94%	91%	77%
7	100%	87%	83%	66%
Avg	100%	$(88 \pm 5)\%$	$(86 \pm 5)\%$	$(71 \pm 6)\%$

4. CONCLUSION

The risk-minimizing TCM that is evaluated in this work reduces the risk to a patient by minimizing the effective dose numerically while maintaining the image quality. The resulting effective dose of riskTCM is reduced up to 35% in comparison to mAsTCM and up to 30% in comparison to osTCM depending on the anatomical region and the patient. Even by comparing the effect of riskTCM on the effective dose of the breast with the effect of osTCM, which is a dose-saving algorithm especially for the breast, riskTCM reduces the effective dose up to 30% more than osTCM because riskTCM accounts for the patient's anatomy.

Table 4: Organ doses for the breast tissue with TCMs.

Pat.	noTCM	mAsTCM	osTCM (25%)	riskTCMopt
1	100%	80%	61%	35%
2	100%	96%	73%	49%
3	100%	93%	69%	37%
4	100%	92%	69%	43%
5	100%	98%	88%	65%
6	100%	93%	71%	47%
7	100%	96%	71%	40%
Avg	100%	$(93 \pm 6)\%$	$(72 \pm 8)\%$	$(45 \pm 10)\%$

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