The impact of vertical off-centering on image noise and breast dose in chest CT with organ-based tube current modulation: A phantom study

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ABSTRACT

Purpose: To determine the effects of patient vertical off-centering when using organ-based tube current modulation (OBTCM) in chest computed tomography (CT) with focus on breast dose.

Materials and methods: An anthropomorphic adult female phantom with two different breast attachment sizes was scanned on GE Revolution EVO and Siemens Definition Edge CT systems using clinical chest CT protocols and anterior-to-posterior scouts. Scans with and without OBTCM were performed at different table heights (GE: centered, ±6 cm, and ±3 cm; Siemens: centered, −6 cm, and ±3 cm). The dose effects were studied with metal-oxide-semiconductor field-effect transistor dosimeters with complementary Monte Carlo simulations to determine full dose maps. Changes in image noise were studied using standard deviations of subtraction images from repeated acquisitions without dosimeters.

Results: Patient off-centering affected both the behavior of the normal tube current modulation as well as the extent of the OBTCM. Generally, both OBTCM techniques provided a substantial decrease in the breast doses (up to 30% local decrease). Lateral breast regions may, however, in some cases receive higher doses when OBTCM is enabled. This effect becomes more prominent when the patient is centered too low in the CT gantry. Changes in noise roughly followed the expected inverse of the change in dose.

Conclusions: Patient off-centering was shown to affect the outcome of OBTCM in chest CT examination, and on some occasions, resulting in higher exposure. The use of modern dose optimization tools such as OBTCM emphasizes the importance of proper centering when preparing patients to CT scans.

1. Introduction

Chest computed tomography (CT) examinations are among the most common CT studies worldwide. Breast tissue is not the target organ in chest CT examination. However, it is one of the most radiosensitive organs in human body and particularly vulnerable to radiation-induced cancer [1]. Therefore, it is important to make efforts to decrease exposure to glandular breast tissue. Several CT optimization methods, both technical and user-dependent approaches, are used to minimize the total radiation dose to the patients and to protect radiosensitive tissues. Technical procedures include tube current modulation (TCM), organ-based tube current modulation (OBTCM), automated tube voltage selection, adaptive beam collimation, beam-shaping filters, and iterative reconstruction techniques [2–15]. External bismuth shields have been used to reduce exposure to radiosensitive tissue, such as breasts and thyroid, but their use in clinical routine has been discouraged [16–19]. Despite the technical solutions for CT optimization, the role of radiographers remains important for achieving optimal results. Several studies have shown harmful effects of patient vertical off-centering on patient dose and image quality due to misalignment of beam-shaping filters and impacts of geometric magnification or minification of patient structures in planning radiographs [20–33]. CT manufacturers have developed technical tools to prevent patient off-centering and to reduce its effects on patient dose and image quality [30,32,34,35].

Recently developed OBTCM methods aim to reduce exposure to radiosensitive tissue by reducing photon flux on the anterior projections during the image acquisition. Technical implementations of OBTCM methods vary between the vendors, for example, in terms of angular organ-dose modulation ranges and the reduction rates of the tube current. Moreover, Siemens approach compensates anteriorly reduced tube current by increasing the current during the posterior projections, whereas GE and Canon approaches do not [6,15,36–38]. In
study. The phantom was set to the CT scanner isocenter by lasers and were not suitable for smaller body phantom model 702-D used in this phantom did not have any internal structures. The custom design was custom-made breasts. The custom-made breasts had a 3D-printed equivalent mixed material (-50 HU at 120 kVp), and larger 500 cc CIRS, Norfolk, VA, USA) was scanned in a supine position with 64-2. Material and methods complexity of combined effects of centering and OBTCM with helical 2.1. Phantom measurements positions varied from 6 cm below to 6 cm above the reference level in 3 different vertical levels of the patient table for the GE system: vertical heights using clinically utilized non-contrast helical chest CT scan pro-mentations differ in similar geometries. Furthermore, due to the complexity of combined effects of centering and OBTCM with helical scanning geometry, the absorbed doses were determined via both Monte-Carlo (MC) simulations as well as measured with metal- oxidesemiconductor field-effect transistor (MOSFET) detectors. The two dose estimation methods were considered complementary: the MOSFET measurements reflected the actual dose accumulation at a limited number of point locations and the MC simulations provided es-timates for more comprehensive volumetric dose distributions. Relative changes in the image noise were reported to aid in reflecting the poten-tial dose savings against changes in the final image appearance.

2. Material and methods

2.1. Phantom measurements

An anthropomorphic adult female phantom (ATOM Model 702-D, CIRS, Norfolk, VA, USA) was scanned in a supine position with 64-slice GE Revolution EVO (GE Healthcare, Milwaukee, Wisconsin, USA) and 128-slice Siemens Definition Edge (Siemens Healthcare, Erlangen, Germany) CT systems. The scans were performed at different table heights using clinically utilized non-contrast helical chest CT scan protocols with and without OBTCM. Each scan was performed with a fixed 120 kVp tube voltage after an anterior-to-posterior (AP) scout image. AP scout was chosen based on Siemens’s recommendation for body region, and the same direction was used with GE for comparability. The large body scan field of view, 64 × 0.625 mm total collimation, noise index of 36 (at 0.625 mm slice thickness), min–max mA range of 10–540 mA, 0.5 s rotation time, 0.984 pitch, and dose reduction of 20% were used in the GE scanner. Similarly, a 128 × 0.6 mm total collimation, quality reference mAs of 120, rotation time of 0.33 s, and 0.6 pitch were used in the Siemens CT system. The anatomical characteristics of the adult female phantom were weight of 55 kg, height of 160 cm, and chest dimensions of 20 × 25 cm without breasts. The chest CT scans were performed with two sizes of breast attachments: smaller 190 cc breasts (702-D-190, CIRS, Norfolk, USA) approximating 50% glandular and 50% adipose equivalent mixed material (-50 HU at 120 kVp), and larger 500 cc custom-made breasts. The custom-made breasts had a 3D-printed polypropylene shell (-150 HU at 120 kVp, 50% of the total volume), which was filled with water (50% of the total volume). The low-density polypropylene shell (thickness approximately 5 mm) acted as a surro-gate for adipose tissue and the water mimicked glandular tissue. The phantom did not have any internal structures. The custom design was based on the models 701- BR-02R and 701- BR-02L CIRS attachments that were not suitable for smaller body phantom model 702-D used in this study. The phantom was set to the CT scanner isocenter by lasers and visual landmarks on the phantom. The scans were performed at five different vertical levels of the patient table for the GE system: vertical positions varied from 6 cm below to 6 cm above the reference level in 3 cm steps. The Siemens system had a limited table height adjustment range, and therefore only four different vertical levels of the patient table (from 6 cm below to 3 cm above the reference level in 3 cm steps) were used. The scan range was set to that of a typical chest CT examination (from the apex of the lungs to the lateral phrenic angles). Equal OBTCM ranges (13 cm) were used for both breast sizes with the GE system. The scanner recorded volume CT dose index (CTDIvol) values were recorded.

Before dose measurements, 12 high-sensitivity TN-1002RD MOSFET dosimeters (Best Medical Canada, Ottawa, ON, Canada) with high-bias settings were calibrated in air for 120-kVp tube voltage using clinical CT beam settings. The calibrations were performed separately for both CT systems in axial scanning mode using 100 mAs exposure. The reference air kerma values in the scan isocenter were measured with a 10-cm pencil ionization chamber (RaySafe Xi, Unfors RaySafe AB, Bill-dal, Sweden). Thereafter, calibration factors for each MOSFET dosimeter were defined separately by repeating measurements five times. The relative standard deviations of the repeated measurements fell in the range from 2% to 6%. A low-dose exposure limit of 1.69 mGy for 25% measurement uncertainty at the 95% confidence level has been reported for this type of MOSFET dosimeter [44]. After the calibration, the dosimeters were placed into and onto the adult female phantom and doses to the lungs (one dosimeter in the right central lung), mediastinum (one dosimeter in heart), and right and left breasts (five dosimeters on the large breasts and four dosimeters on the small breasts on both sides) were measured. Thus, altogether 12 dosimeters were used for the large breast setup and 10 dosimeters for the small breast setup. The dosimeter positions in the lungs, heart, and under the breasts (two dosimeters under each breast) were the same for the small and large breasts, whereas the dosimeter positions above the breast attachments (three dosimeters on large breasts and two dosimeters on small breasts on each side) varied between the breasts (Fig. 1). The scans were repeated three times before reading the dosimeters. This was done to improve the reproducibility of the dose measurements and to achieve sufficiently high radiation doses in the dosimeters. Moreover, this procedure was repeated three times (or total of nine scans) per acquisition setup. The individual dosimeter readings were used to report measurement uncertainty (random error) of the mean absorbed point doses.

2.2. Dose simulations

Absorbed dose maps were estimated using MC simulations (ImpactMC, Vamp GmbH, Germany). The simulations were performed using 3D voxelized data of the complete anthropomorphic phantom with the same imaging configurations as the MOSFET measurements and using 5 × 10⁹ photons. For the final maps, simulations from two X-ray tube starting angles (0° and 180°) were averaged, and the raw dose maps were scaled based on the pencil chamber air kerma measurements performed for the MOSFET calibrations. The anthropomorphic phantom datasets used in the simulations were resampled to 1.5 mm in all three directions to lower the memory requirements. As a prerequisite for the MC simulations, the X-ray spectrum was simulated for 120-kVp tube voltage using Spekcalc 2.0 program [45], and information from the vendor specifications such as tube type, half-value layer, anode material, and filtration were used. Furthermore, beam dose profiles free-in-air were measured for both scanners with the same pencil ionization chamber as used in the MOSFET calibrations to provide source data for beam-shaping filter thicknesses across the axial scan plane. The method used to define the shapes of the beam-shaping filters corresponded to the previously published static X-ray tube method [46]. Bowtie thickness data and simulated spectrum were then used as input for the MC simulations together with the anthropomorphic phantom CT voxel data, scan range, pitch, and angle-specific tube current values. The scan range was matched with the phantom chest acquisitions. Adaptive helical collimation was not incorporated in the simulations. For the GE system, tube current values of the scans performed either with or without OBTCM (ODM, GE Healthcare, Milwaukee, Wisconsin, USA) were
collected from the mA tables shown by the scanner (four mA values reported per rotation, i.e., anterior, left, posterior, and right). A sinusoidal function was fitted to the tabulated mA values to determine the intermediate angle current values used in the MC simulations. In GE Revolution EVO, the dose reduction angle in OBTCM was $180^\circ$, in which the anterior-side projections were scanned with 40% reduced tube current values, while $180^\circ$ of the posterior-side projections were scanned with the same tube current values as would have been the case also without OBTCM. For the Siemens scanner, mean tube current value in each slice was determined from the DICOM header. Thereafter, the mA values used in the MC simulations were calculated using the information from the CT vendor: in Siemens OBTCM method (X-CARE, Siemens Healthcare, Erlangen, Germany), the real-time mA modulation in xy-direction is turned off, $80^\circ$ of the anterior projections are scanned with 25% of the mean tube current, $40^\circ$ of the anterolateral projections ($20^\circ$ on either side of the patient) with 25% to 125% of the mean photon flux (linear ramp, thus the tube current is limited between 25% and 100% of the mean value within the range of $55^\circ$ on either side of the patient), and $240^\circ$ of the posterior projections with 125% of the mean tube current values.

3D absorbed-dose voxel maps were acquired as the output of the simulations. Spherical volumes-of-interest with 15-mm diameters were placed at the corresponding MOSFET dosimeter locations and mean MC doses were recorded. Furthermore, from the simulated 3D dose maps, the average absorbed doses with each scan setup for the breasts, lungs, and mediastinum were determined by subsegments: anterior and lateral for lungs and mediastinum, lateral and medial for large breasts (see for the ROI placement Fig. 1). The breast ROIs covered the whole breasts (with a small margin at the edges). The lung and mediastinum ROIs were limited to the same extent as the large breast attachments. Bones, support structures, and the slices where air between phantom slabs is visible were excluded from the lung and mediastinum ROIs. The values from the corresponding left and right regions (for breasts and lungs) were averaged. Relative changes in the region-of-interest doses were calculated and presented.

2.3. Image noise

The chest CT scans were also performed without MOSFET dosimeters on both CT systems. The scans used the same scan settings and table heights as in the dose measurements. The scans were performed twice at each table vertical height, and subtraction images were then calculated. The image noise values, i.e., standard deviations, were calculated from the same phantom regions as were used in the MC simulation analysis (Fig. 1).

The relative changes in image noise were evaluated from 0.625 mm (GE) and 0.6 mm (Siemens) thick axial reconstructions (512 x 512 pixels) of the phantom. The scans were reconstructed with clinically used reconstruction kernels: the standard reconstruction filter on the GE and the i31f kernel on the Siemens system. Iterative reconstruction was used in all the reconstructions: 40% ASiR-V/filtered back projection blending for the GE and Admire (level 2) for the Siemens. The axial display field of view was adjusted to 35 cm, resulting in a pixel size of 0.683 x 0.683 mm$^2$ in all the images. The mean HU values per individual ROIs (as shown in Fig. 1) were recorded to verify contrast consistency between different acquisitions and setups.

3. Results

3.1. Dosimeter measurements

Patient vertical positioning affected the function of TCM and
anatomical extent of the OBTCM, and thereby the absorbed organ doses, in the chest CT examinations with clear differences between the CT vendors (Fig. 2). In the Siemens scanner, enabling OBTCM increased the reported CTDI\textsubscript{vol} values up to 7% compared to normal TCM chest CT scans, whereas in the GE system, OBTCM decreased the CTDI\textsubscript{vol} up to 17% compared to non-OBTCM scans. The CTDI\textsubscript{vol} values were the highest with the uppermost table height positions, as expected due to geometric magnification in the AP planning radiographs. The relative changes in CTDI\textsubscript{vol} with different vertical levels of patient table compared to 0-cm-level were higher with GE (−22% to +38%, −6 cm to +6 cm) than Siemens scanner (−16% to +12%, −6 cm to +3 cm).

The GE OBTCM reduced organ doses by 10% to 50% compared to non-OBTCM scans, depending on the table height. The highest dose savings were measured on the medial sections of breasts (from 42% to 50%) when the phantoms were positioned above the scan isocenter. The dose-reduction percentages were reduced with lower table height positions. Contrary to GE, Siemens OBTCM increased the right central lung dose from 5% to 25% compared to normal TCM chest CT scans with different vertical positions of patient table. Furthermore, absorbed dose to heart was slightly increased in Siemens OBTCM scans compared to non-OBTCM scans when the phantom was off-centered below the scan isocenter. Impacts of Siemens OBTCM on breast dose varied depending on vertical positioning of the phantom and the selected sections on breast tissue. In general, Siemens OBTCM resulted in higher dose-saving percentages for the breast tissue compared to non-OBTCM scans when the phantom was positioned higher in the gantry. Lateral breast sections, especially above the breast attachments, received higher absorbed doses (up to 10%) with OBTCM than without OBTCM. Only the medial breast

Fig. 2. MOSFET point dose measurements at different vertical positions and phantom setups for GE (A and B) and Siemens scanner (C and D) with and without OBTCM. Zero (0 cm) position is the reference vertical centering level. Breast doses shown in figures at different breast regions are averages over the right and left breasts.
sections received lower doses in all the vertical table levels with OBTCM. The breast size did not affect the general organ-dose level as much in the Siemens as in the GE CT scanner.

3.2. Dose simulations

We compared MC point doses to the corresponding MOSFET dosimeter values (Fig. 3). Due to the approximations used in the protocol modelling (e.g., X-ray spectrum, estimated TCM and OBTCM behavior, bowtie shapes), when compared to the MOSFETs, the MC simulations systematically underestimated the point doses by 20% (the average ratio between the two was 0.80 ± 0.08). However, the relationship was linear (R² = 0.90), which justifies the following investigations based on the relative changes in dose.

According to MC simulations (Table 1), organ doses in chest CT scans with and without OBTCM typically reduced with lower table positions due to geometric minification seen in the AP scout images. This applied to both CT systems. Posterior lung and posterior mediastinum doses varied the most at different vertical table heights. This was mostly because the CT system beam shaping filter assumes cylindrically symmetric target positioned in the isocenter. Vertical off-centering results in angularly varying mismatch between the assumed target attenuation and designed filter thickness. The highest dose-saving percentages with OBTCM methods were observed for the medial breast tissue sections (up to 27% and 30% for GE and Siemens, respectively). The GE OBTCM never increased organ doses compared to non-OBTCM scans, and resulted in organ dose savings of 13% to 27%. However, positioning the phantom below the scan isocenter reduced the dose-saving capability of the method.

Fig. 4 shows visually how enabling OBTCM on the GE scanner reduces the breast doses. Likewise, centering patient too low with AP scout direction reduces the overall dose in general and especially on the posterior side of the patient. In relation to normal TCM chest CT scans, the Siemens OBTCM reduced radiation dose to medial breast tissue approximately a quarter in case of large breasts and one fifth with small breasts when the phantom was positioned vertically on the scan isocenter. However, when lowering the patient table by 6 cm from this, the dose-saving percentages for medial breast sections reduced. At the same time, the portion of lateral breast regions receiving higher doses with OBTCM increased (Fig. 5 and Table 1). Fig. 5 also shows that parts of the lateral breast tissues may lay outside the reduced dose zone of Siemens OBTCM, although the patient would be correctly positioned on the scan isocenter. In Siemens, when positioning the phantom with large breast attachments 6 cm below the scan isocenter, a 16% increase of the mean lateral breast dose was observed with OBTCM scans in relation to non-OBTCM scans.

Differential dose volume histograms from MC simulations are presented in Fig. 6 with the studied vertical centering levels applied to medial (Fig. 6A) and lateral (Fig. 6B) regions of the large breast model. The dose values in the histogram are normalized to dose in air at isocenter, and thus they exclude the net mAs differences in the scans but represent the combined effect of angular intensity of the rotational exposures and phantom alignment on that exposure geometry.

3.3. Image noise

Changes in the image noise were assessed by measuring HU standard deviations inside the ROIs from the repeated-acquisition subtraction images. The relative changes from TCM-only to TCM-with-OBTCM, and from reference centering to different vertical offsets are shown in Table 2. The noise had generally the expected inverse relation to CTDIvol (approximating the average irradiation over the whole imaging volume). Noise increase after off-centering was emphasized for the regions furthest from the isocenter (e.g. anterior regions at high table height). Vertical offset of ± 3 cm from the reference height resulted in noise changes from −12% to 18%. The largest observed increase in noise (36% to 44%) was for the posterior lung when the table was at ~6 cm height for GE scanner. Within ± 3 cm table height range enabling the OBTCM resulted in only minor changes in noise: increase by 5% to 10% for the GE scanner and change from ~7% to 1% for the Siemens scanner. These were approximately in line with the CTDIvol changes from −16% to −12% and from 2% to 7% for GE and Siemens, respectively.

The mean HU values for different acquisitions, tube modulations and centerings were recorded for each individual ROI. The differences between two identical acquisitions (used for the noise estimations) for individual ROIs ranged from −1.1 to 1.0 HU. When comparing OBTCM against TCM-only, the ROI differences ranged from −1.1 to 1.4 HU. When different table heights were compared against the reference vertical centering (0 cm) the ROI mean differences varied from −4.3 to 2.0 HU. The largest absolute difference for the Siemens scanner was observed for the right medial large breast ROI (~4.3 HU at 3 cm table offset without OBTCM). The largest absolute difference for the GE scanner was seen for the posterior mediastinum ROI (~2.3 HU at 6 cm table offset with the large breast attachments, and without OBTCM).

4. Discussion

Breast tissue is one of the most radiosensitive organs in human body [1]. Therefore, special attention should be given to protect glandular breast tissue from the detrimental effects of ionizing radiation in healthcare. The radiation dose for the breasts and for the entire patient can be reduced in CT scans by using various technical optimization tools. Regardless of technical advances, user-dependent practices (e.g. patient positioning into CT gantry) are currently even more important than before in CT optimization as many dose-reduction tools (e.g. bowtie filters, TCM, and automated tube voltage selection methods) assume patients to be positioned properly to scan isocenter. Several studies have reported remarkable variation in patient positioning, especially in vertical direction, resulting in changes in both exposure to patients and image quality [20–29,33]. In this study, the impacts of patient vertical
The relative changes in the average absorbed MC doses measured inside seven regions-of-interest. The reported values are TCM (or OBTCM) at table height \times cm compared to TCM (or OBTCM) at 0 cm; and OBTCM wrt TCM at the same table height. The absolute absorbed dose values (mean \pm standard deviation over the ROI) and the average tube currents (mA) used in the simulations are reported for the reference height 0 cm (gray background). The mGy values are scaled by factor 1.25 (=1/0.8 in Fig. 3) to better match the more conservative MOSFET measurements. Abbreviations: wrt: with respect to; TCM: tube current modulation (without OBTCM); OBTCM: organ-based tube current modulation enabled (with normal TCM).

| Setup for dose simulations | Lateral large breast | Medial large/small breast | Mediastinum anterior | Mediastinum posterior | Lungs anterior | Lungs posterior | Average tube current |
|---------------------------|----------------------|---------------------------|----------------------|----------------------|---------------|-------------------|---------------------|
|                           | TCM                  | OBTCM                    | OBTCM                | TCM                  | OBTCM         | OBTCM            | TCM                 |
|                           | wrt 0 cm             | wrt TCM                  | wrt 0 cm             | wrt TCM              | wrt 0 cm      | wrt TCM          | wrt 0 cm            |
| GE                        |                      |                           |                      |                      |               |                   |                     |
| Large breast              |                      |                           |                      |                      |               |                   |                     |
| 6 cm                      | 18%                  | 15%                       | –24%                 | 4%                   | 2%            | –27%              | 12%                 |
| 3 cm                      | 9%                   | 7%                        | –23%                 | 1%                   | 0%            | –26%              | 8%                  |
| 0 cm                      | 4.6 ± 3.6 mGy        | 5.2 ± 3.9 mGy            | 5.9 ± 4.6 mGy        | 5.8 ± 4.9 mGy        | 5.7 ± 4.6 mGy | –20%              | 6.0 ± 5.0 mGy        |
| Small breast              |                      |                           |                      |                      |               |                   |                     |
| 6 cm                      | –3 cm                | –18%                      | –21%                 | –1%                  | –3%           | –24%              | –10%                |
| 3 cm                      | –6 cm                | –18%                      | –21%                 | –4%                  | –3%           | –24%              | –21%                |
| 0 cm                      | –6 cm                | –18%                      | –21%                 | –4%                  | –3%           | –24%              | –21%                |
| Siemens                   |                      |                           |                      |                      |               |                   |                     |
| Large breast              |                      |                           |                      |                      |               |                   |                     |
| 3 cm                      | 5.1 ± 5.3 mGy        | 5.6 ± 4.3 mGy            | 6.4 ± 5.7 mGy        | 6.3 ± 5.7 mGy        | 6.3 ± 5.7 mGy | 20%               | 6.1 ± 6.3 mGy        |
| 0 cm                      | –3 cm                | –6%                       | –12%                 | –3%                  | –4%           | –13%              | 13%                 |
| Small breast              |                      |                           |                      |                      |               |                   |                     |
| 3 cm                      | –6 cm                | –11%                      | –2%                  | –2%                  | –14%          | –30%              | –18%                |
| 0 cm                      | –6 cm                | –11%                      | –2%                  | –2%                  | –14%          | –30%              | –18%                |

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off-centering on the function of recently developed OBTCM techniques, and further on breast dose, were examined by using two CT systems from different vendors and two sizes of breast attachments applied for the anthropomorphic female body phantom.

Previous studies have shown OBTCM to significantly reduce breast dose in chest CT [6,15,36,37,39,42,47]. However, the real anatomy of patients’ breasts in supine position can be very different from what has been seen in the phantom studies or when patient is in a standing or sitting position. Thus, part of the breasts may be drooping aside the chest and become vulnerable for higher exposure in chest CT. In this study, both the dose measurements and MC simulations revealed that breast dose, especially in lateral breast sections, may be increased in chest CT.

Fig. 4. MC dose simulations of the GE scanner at the optimal centering (0 cm; A and B) and by lowering the table by 6 cm (C and D) without OBTCM (A and C) and with OBTCM (B and D).

Fig. 5. MC dose simulations of the Siemens scanner at the optimal centering (0 cm; A and B) and by lowering the table by 6 cm (C and D) without OBTCM (A and C) and with OBTCM (B and D). The competing effects from mispositioning (between A and C: increased dose in the fronto-medial region) and OBTCM (between C and D: decreased dose in the frontal angle) is well visualised.
scans if the patient is not properly centered to the scan isocenter. Patient off-centering was shown to affect the function of OBTCM. For Siemens CT, the results showed that parts of the breast tissue may actually be exposed to higher amount of radiation dose when OBTCM is used compared to chest CT scans performed only with conventional TCM method. This results from the fact that Siemens is boosting photon flux from the posterior-side projections to maintain image noise. The tube-current boosting increased the overall scan CTDI<sub>vol</sub> up to 7%. The GE OBTCM method did not increase the breast dose nor any other organ doses at any vertical positions of a patient table. Moreover, the CTDI<sub>vol</sub> was decreased up to 17% in GE OBTCM chest CT scans compared to TCM-only scans, resulting in increased image noise to the images. If the image noise needs to be unchanged, the GE noise index should be decreased in OBTCM scans. This would correspondingly lead to an increased dose outside the OBTCM activated scan range. The differences in breast doses between the CT vendors OBTCM solutions can be explained by the corresponding differences in the OBTCM reduced dose angular ranges (projections with reduced photon flux) and distance range limits in z-direction. GE has a user-adjustable z-range coverage for the OBTCM function, whereas Siemens applies OBTCM for the entire scan range. More crucially for this study, a wider dose-reduction angular range was used in the GE system compared to that of Siemens. According to the manufacturer, 180° of the anterior-side projections are scanned with 40% reduced tube current values in GE Revolution EVO system while 180° of the posterior-side projections are scanned with the same tube current values as would be the case without OBTCM. In Siemens OBTCM solution, 80° of the anterior-side projections are scanned with 75% lower to 25% higher tube currents, and 240° of the posterior-side projections with 25% increased tube current values compared to a scan performed without OBTCM. Some differences between the vendors, as well as mismatch between the MOSFET and (idealized) MC doses may also arise from the OBTCM performance dependence on the imaging parameters. For example, increasing tube rotational velocity has been reported to decrease the angular range of the reduced exposure window [48]. The dose calculations involved several other sources of uncertainties which were related to the simulation software, the applied x-ray source models (e.g. bowtie filter, spectra and helical scan exposure geometry), material conversion, and the anthropomorphic phantom model. According to a previous study with similar methodology, the maximum difference between dose measurement and simulation results was found to be around 15% as applied to phantom data with ImpactMC program incorporating bowtie filter and spectra models [49]. Higher uncertainties can be anticipated if simulations are performed for clinical patient data with individual morphology, organ locations and shapes.

Studies have shown that parts of the glandular breast tissue are usually left outside the dose-reduction zone in Siemens OBTCM solution [12,36,38]. Our study showed that patient off-centering below the scan isocenter worsened the situation and increased the breast dose further. This is also presented in Fig. 6 showing differential dose-volume histograms of the lateral and medial large breast regions with dose normalized to air kerma measured at isocenter, and a fixed bin width was used in all the histograms.

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**Fig. 6.** Differential dose-volume histograms at different vertical centering in the A) medial breast and B) lateral breast region of the large breast phantom setup for GE (left hand side) and Siemens (right) scanner. The corresponding left and right breast regions are combined. The values are normalized to air kerma measured at isocenter, and a fixed bin width was used in all the histograms.
Table 2
The relative percentage changes in noise measured inside seven regions-of-interest. The reported values are TCM (or OBTCM) at table height \( \times \text{cm} \) relative to TCM (or OBTCM) at 0 cm; and OBTCM relative to TCM at the same table height. Absolute noise values and CT dose indices are reported for the reference table height 0 cm (gray background). Abbreviations: wrt: with relative to; TCM: tube current modulation (without OBTCM); OBTCM: organ-based tube current modulation enabled (with normal TCM).

| Setup for noise measurements | Lateral large breast | Medial large/small breast | Mediastinum anterior | Mediastinum posterior | Lungs anterior | Lungs posterior | CT Dose Index |
|------------------------------|----------------------|---------------------------|----------------------|----------------------|---------------|----------------|---------------|
| GE                           | TCM wrt 0 cm | ORTCM wrt 0 cm | ORTCM wrt TCM | TCM wrt 0 cm | ORTCM wrt 0 cm | ORTCM wrt TCM | TCM wrt 0 cm | ORTCM wrt 0 cm | ORTCM wrt TCM | TCM wrt 0 cm | ORTCM wrt 0 cm | ORTCM wrt TCM | TCM wrt 0 cm | ORTCM wrt 0 cm | ORTCM wrt TCM | TCM wrt 0 cm | ORTCM wrt 0 cm | ORTCM wrt TCM | TCM wrt 0 cm | ORTCM wrt 0 cm | ORTCM wrt TCM |
| Large breast                 |                     |                           |                      |                     |               |               |                     |               |               |                     |               |               |               |                     |               |               |                     |               |               |                     |               |               |                     |               |               |                     |
| 0 cm                         | 6 cm                 | 4%                        | 4%                   | 6%                   | 15%           | 15%           | 7%                   | -1%           | 0%            | 9%                   | -14%           | -12%           | 7%                   | 5%            | 6%            | 10%                   | -16%           | -16%           | 9%                   | 38%           | 36%           | -17%                   |
| -3 cm                        | 1%                   | 0%                        | 5%                   | 4%                   | 4%            | 7%            | -3%                   | -2%           | 9%            | -7%                   | -6%            | 6%            | 0%                   | 0%            | 10%           | -11%                   | -10%           | 10%           | 17%                   | 15%           | 16%           | -16%                   |
| -6 cm                        | 13%                  | 4%                        | 5%                   | 6%                   | 4%            | 5%            | 10%                   | 9%            | 6%            | 23%                   | 20%           | 3%            | 20%                   | 17%           | 7%            | 44%                   | 41%           | 6%            | -22%                   | -22%           | 15%           | -15%                   |
| 6 cm                         | -3 cm                | 0%                        | 6%                   | 0%                   | 0%            | 6%            | 5%                   | 4%            | 7%            | 9%                   | 7%            | 5%            | 8%                   | 6%            | 7%            | 18%                   | 17%           | 7%            | -12%                   | -12%           | -15%          | -15%                   |
| 3 cm                         | -6 cm                | 11%                       | 4%                   | 11%                  | 13%           | 9%            | -1%                   | -1%           | 9%            | -12%                   | -10%          | 7%            | 9%                   | 11%           | 10%           | -14%                   | -13%          | 10%           | 33%                   | 32%           | -13%          | -13%                   |
| Small breast                 |                     |                           |                      |                     |               |               |                     |               |               |                     |               |               |                     |               |               |                     |               |               |                     |               |               |                     |
| 0 cm                         | 6 cm                 | 3%                        | 5%                   | 4%                   | 5%            | 8%            | -1%                   | -1%           | 7%            | -5%                   | -5%           | 5%            | 2%                   | 1%            | 9%            | -9%                   | -9%           | 8%            | 14%                   | 14%           | -13%          | -13%                   |
| -3 cm                        | 1%                   | 0%                        | 7%                   | 0%                   | 0%            | 7%            | 4%                   | 4%            | 7%            | 6%                   | 7%            | 5%            | 9%                   | 15%           | 7%            | -12%                   | -11%          | -12%          | -12%                   |
| -6 cm                        | -6 cm                | 6%                        | 5%                   | 6%                   | 4%            | 5%            | 9%                   | 8%            | 6%            | 22%                   | 19%           | 3%            | 18%                   | 15%           | 7%            | 40%                   | 36%           | 5%            | -21%                   | -20%          | -12%          | -12%                   |
| Siemens                      |                     |                           |                      |                     |               |               |                     |               |               |                     |               |               |                     |               |               |                     |               |               |                     |               |               |                     |
| Large breast                 |                     |                           |                      |                     |               |               |                     |               |               |                     |               |               |                     |               |               |                     |               |               |                     |               |               |                     |
| 0 cm                         | 3 cm                 | 4%                        | 4%                   | -4%                  | 8%            | 8%            | -4%                   | 4%            | -3%           | -5%                   | -4%           | 1%            | 2%                   | 4%            | -4%           | -3%                   | -2%           | 1%            | 6%                   | 8%            | 7%            | 7%                   |
| -3 cm                        | 2%                   | -5%                       | -4%                  | 2%                   | 1%            | -4%           | 11%                   | 10%           | -1%          | 6%                   | 5%            | -6%           | 11%                   | 9%            | -3%           | -9%                   | -8%           | 7%            | -16%                   | -15%          | 7%            | -15%                   |
| -6 cm                        | 11%                  | -5%                       | -4%                  | 0%                   | 0%            | -4%           | 7%                   | 6%            | -4%           | 25%                   | 23%           | -2%           | 15%                   | 14%           | -6%           | 26%                   | 24%           | -4%           | -16%                   | -15%          | 7%            | -16%                   |
| 3 cm                         | -6 cm                | 4%                        | -3%                  | 0%                   | 2%            | -2%           | -7%                   | -4%           | 3%            | 0%                   | 3%            | -4%           | -6%                   | -2%           | 1%            | 12%                   | 9%            | 2%            | 3.4                   | 3.5 mGy        | 5%            | 3.4                   |
| Small breast                 |                     |                           |                      |                     |               |               |                     |               |               |                     |               |               |                     |               |               |                     |               |               |                     |               |               |                     |
| 0 cm                         | -3 cm                | -1%                       | -5%                  | 2%                   | 3%            | -4%           | 12%                   | 10%           | -2%          | 5%                   | 4%            | -7%           | 11%                   | 9%            | -5%           | -10%                   | -8%           | 7%            | -16%                   | -15%          | 7%            | -15%                   |
| -6 cm                        | -6 cm                | 3%                        | -4%                  | 7%                   | 8%            | -3%           | 25%                   | 22%           | -3%           | 13%                   | 13%           | -7%           | 26%                   | 24%           | -6%           | -16%                   | -15%          | 7%            | -15%                   |
accentuated in medial breast region (Fig. 6A) which is closer to the isocenter as compared to lateral region. Further, the histogram peak is wider in medial region (especially with Siemens) on the lowest (-6 cm) vertical position when OBTCM is not used. On the other hand, for the lateral breast region (Fig. 6B) the dispersion of the histogram peak positions is higher across the vertical levels (combined with somewhat wider histogram peaks) with Siemens scanner when OBTCM is used. This reflects the narrower reduced angular dose range which does not extend to the lateral breast part. Consequently, the lateral breast region receives more heterogeneous dose distribution (represented by histogram peak width) and larger variance of histogram peak positions between different vertical levels. Such effect is not observed with lateral breast regions with GE scanner with wider angular OBTCM dose reduction zone or with Siemens when OBTCM is not used. As noted above, information shown in the Fig. 6 offer additional explanatory geometrical aspects of dose which are not obvious from the Table 1 involving relative changes in the mean doses in specified organ regions.

The study results showed image noise to be maintained or reduced with Siemens OBTCM while increased with GE approach when positioning the patient to the scan isocenter. The image noise results were approximately following the Poisson statistics. Image noise altered when positioning the phantom either above or below the scan isocenter. The change in image noise was a combination of changes observed in CTDIvol and functions of beam-shaping filters and OBTCM techniques. Siemens CT systems are known to use flatter beam-shaping filters than GE systems, and therefore the impacts of vertical off-centering on image noise were stronger in GE chest scans. When considering other image quality aspects, Fu et al. [15] discussed that a potential artifact with GE OBTCM method could be induced by photon starvation especially in the shoulder region or for patients with metal implants in clinical cases. We did not observe photon starvation induced artefacts in our phantom study (which did not involve metal implants). To summarize the contrast value changes: repeating a scan or enabling the OBTCM did not show surface dose to increase by up to 18% and 49% when a 32 cm cylindrical CTDI phantom was off-centered 3 cm and 6 cm below the isocenter, respectively. Kaasalainen et al. [23] reported increased breast doses of up to 16% when off-centering a pediatric five-year-old anthropomorphic phantom 6 cm below the scan isocenter in chest CT using a fixed tube current value. Saltysbaeva and Alkadhi [27], on the other hand, observed 38% increase in thyroid dose when off-centering an anthropomorphic phantom by 5 cm. Euler et al. [40] found in their simulations for a Siemens CT system using OBTCM in chest CT that breast dose increased up to 11% when off-centering a patient 1.8 cm below the scan isocenter. They also reported significantly higher relative doses to breasts for 75 years and older patients compared with younger patients. They assumed this to be related to aging process of breasts, leading to lower elasticity of the subcutaneous tissue, and therefore, resulting in a lateral drooping of the breasts in the supine position. This causes larger amount of glandular tissue to be positioned in the increased TCM than with OBTCM in chest CT examinations.

Some of the previous studies have claimed the potential benefits of Siemens OBTCM technique to be overestimated in chest CT. For example, Frank et al. [38] stated that dose reduction to breasts may actually be less than 10% due to a limited tube-current reduction zone whereas posterior organs may absorb up to more than 25% more radiation, resulting in no reduction of radiation-induced malignancies. This observation was similar to our study results, as we found a 20% to 25% increase in the posterior mediastinum and posterior lung region doses in our MC simulations. Mussmann et al. [43] also reported that Siemens OBTCM may not automatically be advantageous for the patients by observing higher breast doses with OBTCM than without it. They assumed this to be related partly on the lower pitch value used in the OBTCM chest CT protocol. Also, Layman et al. [47] observed that some females received higher breast doses with Siemens OBTCM than without it. One of the main reasons for this was lateral sections of glandular breast tissue being outside the dose reduction zone of the OBTCM and instead in the boosted tube current zone.

This study has certain limitations. First and foremost, the study geometry was limited to only one relatively lean anthropomorphic phantom with two sizes of breasts. Considering the diversity in the anatomic characteristics, breast size, and body mass index among women, considerable variation can be anticipated in dosimetric and image noise estimations in different patient morphologies. The anthropomorphic phantom used in this study represented particularly small female patients with chest dimensions being without breasts attachments 20 cm × 25 cm. In larger patients, a higher portion of glandular breast tissue can be left outside the dose-reduction zone in Siemens OBTCM. Secondly, only two CT scanners from two vendors were examined. Third, the conclusions from this study might not be generalizable to other implementations, different OBTCM angles and dose-reduction percentages. For example, GE uses different dose reduction angles in different CT models. Also, the CT scanners used in this study did not have automatic patient table positioning systems, which could potentially reduce the centering errors resulting in smaller dose and image quality variations between operators and patients. Third major limitation was that only acquisitions with AP scouts were studied. Lateral, posterior-to-anterior (PA) and AP scouts result in different geometric magnifications (especially for the spine), and therefore may have differing TCM dependences on the vertical off-centering magnitude as well as direction. According to a previous study, using the PA instead of AP scout direction resulted in higher breast doses when positioning the patient below the scan isocenter [33]. The lateral scout direction resulted in less dose variation when off-centering the patient but suffered from higher image noise than acquisitions with PA or AP scouts [24,33]. Similar differences in behavior can be expected with OBTCM. Fourth, the organ doses were determined as average readings from the limited number of point measurements with MOSFET dosimeters. However, the voxel-based Monte Carlo simulations supported the findings of MOSFET measurements and yielded more comprehensive analysis of breast dose in varying off-centering levels. Also, not all radiosensitive organs and tissues (e.g. thyroid) were included in the dosimetric evaluation as the focus was mainly on the breast doses. Fifth, we did not have access to projection-specific tube current values on the CT systems, but the mA values used for MC simulations were determined using the information received from the CT vendors. Lastly, the noise was investigated by only considering HU variation and only limited contrast changes were considered. In general, image quality could also be affected by varying artefact strengths and changes in the noise textures. Estimating true clinical impact would require clinically relevant diagnostic tasks with realistic ranges of imaging target contrast levels, shapes, and sizes.

Proper patient centering is an important factor from both dose optimization and image quality perspectives. These effects may be further emphasized when using OBTCM. Potential issues could be mitigated by proper choice of imaging parameters, such as scout direction, paying attention to proper centering in vocational training, or utilizing automatic patient table positioning systems [34,35]. Future studies combining clinical images, relevant diagnostic tasks, and individual radiation doses are warranted to estimate the true clinical impact of various technical solutions.

5. Conclusion

Despite the CT vendors introducing novel CT optimization tools for dose reduction, users should be aware of their technical
implementations and limitations. The results of this study provide a cautionary note for the notable differences between two vendors’ OTBCM implementations with direct consequences on dose and image noise. Specifically, patient off-centering was shown to affect the outcome of OTBCM in chest CT examination, and on some occasions, resulting in higher exposure. The use of modern dose optimization tools, such as OTBCM, emphasizes the importance of proper centering when preparing patients to CT scans.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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