Current Problems in Diagnostic Radiology 48 (2019) 229–234

Current Problems in Diagnostic Radiology

journal homepage: www.cpdrjournal.com

Prevalence and Severity of Off-Centering During Diagnostic CT: Observations From 57,621 CT scans of the Chest, Abdomen, and/or Pelvis

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Purpose: To determine distances between patient centroid and gantry isocenter during CT imaging of the chest, abdomen, and/or pelvis, and to evaluate differences based on patient gender, scan region, patient position, and gantry aperture.
Materials and Methods: A water phantom and an anthropomorphic phantom were imaged in the centered position in the CT gantry and at several off-centered positions. Additionally, data from 57,621 adult chest, abdomen, and/or pelvic CT acquisitions were evaluated. Data were analyzed with an analysis of variance using the centroid-to-isocenter data as the dependent variable and the other parameters as independent variables.
Results: The majority of patient acquisitions (83.7% (48271/57621)) were performed with the patient's centroid positioned below isocenter (mean 1.7 cm below isocenter (SD 1.8 cm); range 12.1 cm below to 7.8 cm above isocenter). Off-centering in the x-axis was less severe (mean 0.01 cm left of isocenter (SD 1.6 cm)). Distance between centroid and isocenter in the y-axis did not differ as a function of sex but did differ based on scan region, patient position, and gantry aperture.
Conclusion: Off-centering is common during CT imaging and has been previously demonstrated to impact dose and image quality.

Introduction

Computed tomographic (CT) imaging utilization continues to increase.[1-4] Per capita radiation dose in the United States has nearly doubled in the past 20 years primarily due to CT imaging.[4] A variety of technologies have been developed to decrease radiation exposure including automated tube current modulation and tube voltage selection software.[5-7] Bow-tie filters can also decrease radiation exposure by shaping the x-ray beam to attenuate the x-rays delivered to the less attenuating periphery of the patient, while still delivering sufficient x-rays to the more attenuating center of the patient.[8-10]

However, prior investigations have shown that patient off-centering in the CT gantry can impact dose due to (1) magnification effects in the topogram with use of topogram-based tube current modulation and tube voltage selection software and (2) malalignment with the x-ray beam shape with use of a bow-tie filter.[8-18] A linear relationship exists between the distance separating the topogram x-ray source and the patient and the resultant magnification in the topogram.[12,16] If the patient is off-centered closer to the x-ray source for the topogram, the patient's magnified size in the topogram will result in selection of higher maximum tube currents and tube voltages than would be selected based on the patient's true size.[11,12,16] When patients are off-centered in the CT gantry and a bow-tie filter is employed, more x-rays than necessary are delivered to the periphery of the patient with surface dose increased by 12%-49%.[9] Prior investigators evaluating relatively small patient series ($n = 63$-549) found that when centering based on a visual estimate, patients were off-centered by a mean of 2.1-2.3 cm below isocenter during chest and body CT[8,15] and a median of 2.5-3.5 cm below isocenter during chest CT.[14]

The purpose of this investigation was to evaluate a database containing data from more than 56,000 CT acquisitions to determine the prevalence and severity of patient centroid off-centering during CT imaging of the chest, abdomen, and/or pelvis using commercially available software (Radimetrics Enterprise Platform (Bayer AG, Leverkusen, Germany)), and to assess for differences based on patient sex or size, scan region, patient position, and gantry aperture. Additionally, we determined how computed patient centroid to CT gantry isocenter distances were compared to empirical values.

Materials and Methods

Institutional Review Board approval was obtained for this Health Insurance Portability and Accountability Act compliant study.

The authors have no financial conflicts of interest to declare.
No funding sources were used for this project.

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https://doi.org/10.1067/j.cpradiol.2018.02.007
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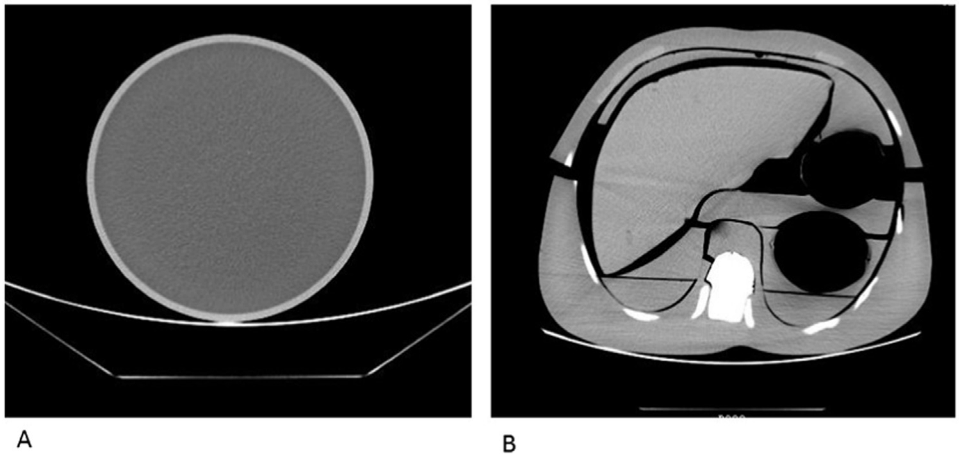

FIG 1. (A) Water phantom. (B) Anthropomorphic phantom.

Phantom Study

A water phantom and an anthropomorphic phantom (Fig 1) were imaged using a Lightspeed 64-MDCT VCT (GE Healthcare, Chicago, IL). The water phantom was the daily quality assurance phantom (GE Healthcare). The anthropomorphic phantom was a modified Livermore phantom (Pacific Northwest National Lab, Richland, WA) of the thorax and abdomen.[19-21] The phantom simulates a male cadaver anthropomorphically, 1.01 m in chest circumference, 75 kg in weight, and 1.77 m in height.[20] The major organs were duplicated with tissue-equivalent substitutes.[20] Images were acquired using automated tube current modulation (noise index 10.0, minimum 10 mA, maximum 800 mA, 120 kVp, 5 mm section thickness).

To center each phantom in the gantry, the anterior-posterior midpoint of the phantom was measured and marked, and the laser lights of the CT gantry were aligned with this midpoint. The laser lights were assessed for accuracy prior to imaging. Images were acquired with each phantom centered in the CT gantry as well as at −6 cm, −3 cm, +3 cm, and +6 cm relative to the centered position (Fig 2). The resultant images were imported into Radimetrics, which computed the distance between centroid and isocenter for each table position. Differences between table positions (+3 cm, +6 cm, etc.) and computed centroid-to-isocenter values were compared for the water and anthropomorphic phantoms. The topogram was acquired with anterior-posterior technique for each acquisition.

CT dose index and dose length product were recorded for each phantom at each offset. Image quality was assessed by measuring the standard deviation of Hounsfield units in a 2.0 cm^2 region of interest in the center of the water phantom and in a homogeneous soft tissue area of the anthropomorphic phantom.

Retrospective Patient Study

Data from consecutive single phase adult CT scans of the chest, abdomen, and/or pelvis, performed in our health care system during 2015 and 2016 and using equipment manufactured by General Electric, were extracted for review using the Radimetrics Enterprise Platform. These CT examinations were performed using the Lightspeed VCT 64-MDCT ($n = 4$ machines), Discovery CT750 HD 64-MDCT ($n = 3$), Lightspeed 16-MDCT ($n = 3$), Brightspeed 16-MDCT ($n = 2$), Lightspeed 8-MDCT ($n = 1$), and Discovery 600 ($n = 1$).

Patient sex, region imaged, patient position (e.g., prone, supine, or decubitus), and specific CT device were recorded. Studies performed using a biopsy protocol or with the patient in the decubitus position were excluded. The distances between the patient′s centroid and the CT gantry isocenter in the x-axis and y-axis as computed by Radimetrics were recorded. According to the vendor, the centroid to isocenter x-axis and centroid to isocenter y-axis values reflect the average distance between the centroid and the isocenter for all axial images.

For each axial image, the Hounsfield units are converted by Radimetrics to a material density, and the material density is used to calculate the center of mass of the body cross-section. By convention, the y-axis increases toward the back of the patient in the supine position. When a patient is in the supine position, a positive centroid to isocenter distance indicates that the patient is closer to the floor. A negative centroid to isocenter distance indicates that the patient is closer to the ceiling if the patient is in the supine position. Also by convention, the x-axis increases toward the left hand side of the patient such that a positive centroid to isocenter distance indicates that the patient is offset to the left of center, and a negative centroid to isocenter distance indicates that the patient is offset to the right of center. Mean patient diameter as computed by Radimetrics was recorded and reflects the average patient diameter computed from the axial CT images.

Descriptive statistics were utilized to evaluate the prevalence and severity of off-centering. The data were analyzed with an analysis of variance (ANOVA) with Protected Least Squares Difference (PLSD) post hoc tests using the centroid-to-isocenter data as the dependent variable and the other parameters as independent variables.

Results

Phantom Study

Distances between phantom centroid and gantry isocenter are reported for the water phantom and the anthropomorphic phantom in Tables 1 and 2. For the water phantom, computed centroid-to-isocenter distances were very similar to the geometric center of the phantom, likely due to homogeneity of the water phantom such that the geometric center of the phantom was essentially equivalent to the phantom′s centroid. However, for the anthropomorphic phantom, the computed centroid-to-isocenter distance was consistently lower than the geometric center of the phantom (Table 2), likely due to the presence of more attenuating structures

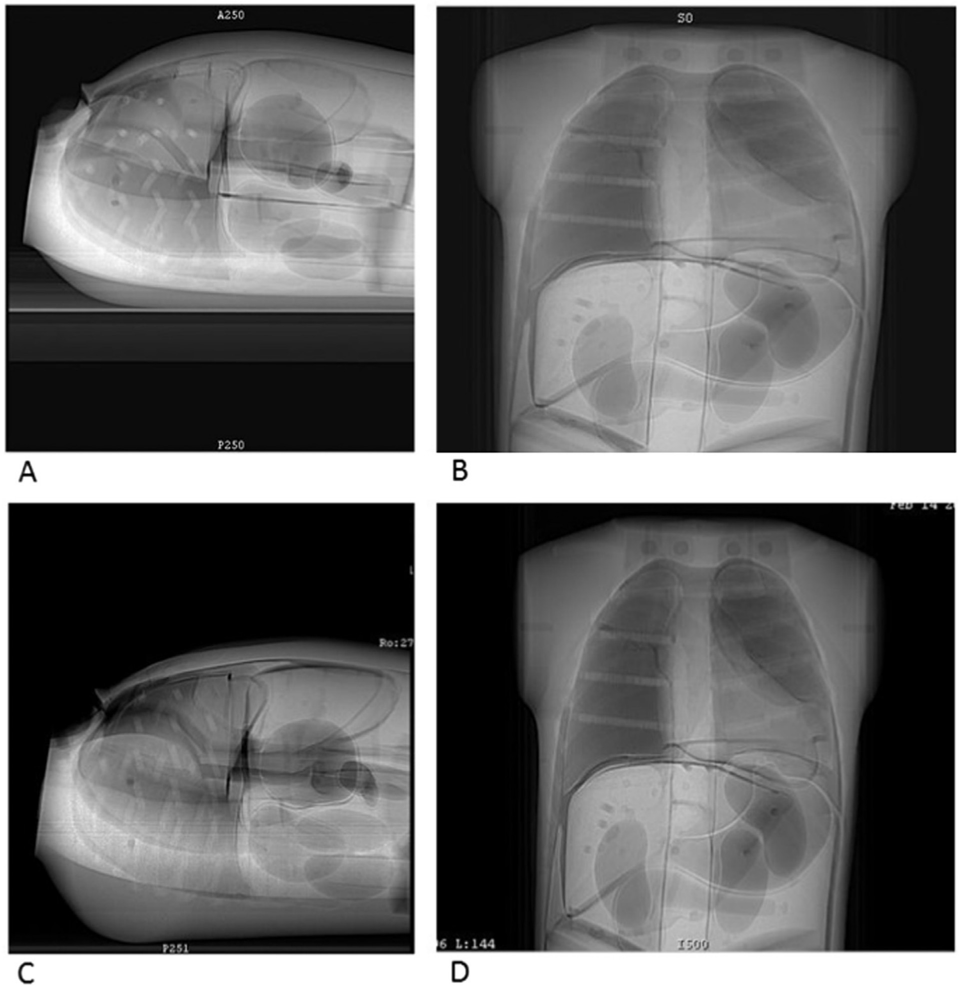

FIG 2. Phantom offsets. (A) Lateral topogram with phantom positioned 6 cm above the centered position. (B) Frontal topogram obtained with anterior-posterior technique with phantom positioned 6 cm above the centered position. (C) Lateral topogram with phantom positioned 6 cm below the centered position. (D) Frontal topogram obtained with anterior-posterior technique with phantom positioned 6 cm below the centered position.

(e.g., simulated vertebral bodies) in the posterior aspect, or air gaps in the anterior aspect, of the phantom.

As each phantom was positioned closer to the x-ray source for the anterior-posterior topogram, the phantoms appeared magnified, and measures of dose (CTDIvol and DLP) increased (Tables 1 and 2). By comparison, when either phantom was positioned farther from the x-ray source of the anterior-posterior topogram, the phantom appeared smaller in the topogram and lower doses were observed (Tables 1 and 2). Image noise decreased with higher radiation dose (Tables 1 and 2). Image noise was less for the 3 cm above and 6 cm above center positions as compared to the centered position. Image noise increased for the table positions that were below the centered position (Tables 1 and 2).

Retrospective Patient Study

Data from 57,621 consecutive adult single phase CT examinations were evaluated (57.7% females; 42.3% males). The distribution of distances between patient centroid and gantry isocenter in

TABLE 1
Computed centroid to isocenter distances for water phantom

Water phantom					
Table height (mm)*	Table position offset (cm)†	Centroid to isocenter y-axis (cm)¥	CTDIvol (mGy)	DLP (mGy cm)	Noise (mean SD HU (SD))
48.5	+6.0	−5.1	9.90	144.79	8.7 (0.4)
78.5	+3.0	−2.9	8.72	127.50	9.3 (0.4)
108.5	Centered	+0.3	7.76	113.52	10.2 (0.6)
138.5	−3.0	+3.0	6.94	101.51	10.9 (0.6)
168.5	−6.0	+5.9	6.26	91.58	11.9 (0.6)

* In reference to a position in the top of the CT gantry.
† Manually positioned, relative to centered position.
¥ Computed by radimetrics.

TABLE 2
Computed centroid to isocenter distances for anthropomorphic phantom

Anthropomorphic phantom					
Table height (mm)*	Table position offset (cm)†	Centroid to isocenter y-axis (cm)¥	CTDIvol (mGy)	DLP (mGy cm)	Noise (mean SD HU (SD))
84.5	+6.0	−2.1	31.32	864.99	6.3 (0.6)
114.5	+3.0	+0.8	27.94	778.66	6.7 (1.1)
144.5	Centered	+3.9	24.23	681.39	9.3 (2.5)
174.5	−3.0	+6.6	20.65	575.55	14.2 (1.0)
204.5	−6.0	+8.0	18.03	502.44	21.9 (3.5)

* In reference to a position in the top of the CT gantry.
† Manually positioned, relative to centered position.
¥ Computed by radimetrics.

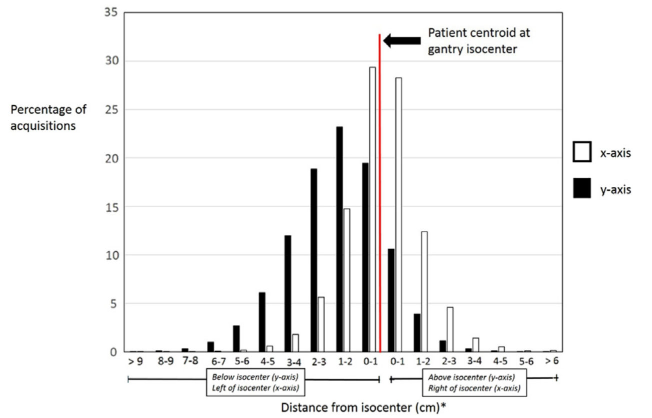

FIG 3. Distribution of distances between patient centroid and gantry isocenter for 57,621 CT acquisitions of the chest, abdomen, and/or pelvis.

the x-axis and y-axis is shown in Figure 3. The majority of acquisitions (83.7% (48271/57621)) were performed with the patient's centroid positioned below the isocenter, and 16.3% (9351/57621) were performed with the patient's centroid positioned above the isocenter (Fig 3). A majority of exams (61.5%) were performed with the patient centroid positioned 0-3 cm below isocenter (Table 3) (Fig 4).

Mean distance from centroid to isocenter in the x-axis was 0.01 cm to the left of isocenter (sd 1.6 cm). A majority of patients (52.5% (30263/57621)) were centered to the left of isocenter, and 47.5% (27359/57621) of patients were centered to the right of isocenter. The percentage of examinations with the patient's centroid located 0-3 cm to the left of isocenter, 3-6 cm to the left of isocenter, and > 6 cm to the left of isocenter was 49.7% (28661/57621), 2.6% 1502/57621, and 0.1% (100/57621), respectively. The percentage of exams with the patient's centroid located 0-3 cm to the right of isocenter, 3-6 cm to the right of isocenter, and 3-6 cm to the right of isocenter was 45.3% (26079/57621), 2.1% (1186/57621), and 0.2% (94/57621), respectively.

The distance between centroid and isocenter in the y-axis did not differ significantly (F = 0.054, $P = 0.8167$) as a function of sex: male mean = 1.7 cm below isocenter (sd = 1.8); female mean = 1.7 cm below isocenter (sd = 1.8). The distance between centroid and isocenter in the x-axis differed significantly (F = 15.299, $P < 0.0001$) as a function of sex: male mean = 0.06 cm left of center (sd = 1.5); female mean = 0.1 cm left of center (sd = 1.5). Although statistically significant, this difference was small.

Mean centroid to isocenter distances based on scanned region (chest = C, abdomen = A, pelvis = P) are reported in Table 4. For all scanned regions and all combinations of scanned regions, patients were centered on average below the isocenter of the CT gantry (range: 1.37-1.89 cm below isocenter) (Table 4). Distance between patient centroid and gantry isocenter in the y-axis differed significantly (F = 114.634, $P < 0.0001$) as a function of scan region, with all comparisons significant except A vs C; CAP vs P, CA; P vs AP, CA; AP vs CA.

TABLE 3
Distribution of patient positions in the y-axis

Patient centroid position	Percentage of exams
> 6 cm above center	< 0.1% (12/57621)
3-5.99 cm above center	0.5% (291/57621)
0-2.99 cm above center	15.7% (9048/57621)
0-2.99 cm below center	61.5% (35423/57621)
3-5.99 cm below center	20.8% (11972/57621)
> 6 cm below center	1.5% (876/57621)

Patients were less off-centered in the x-axis as compared to the y-axis for all scanned regions. Patients were on average slightly off-centered to the right (0.01 and 0.04 cm) for CTs of the chest, abdomen, and pelvis and for CTs of the pelvis and were slightly off-centered to the left (0.03 to 0.21 cm) for other scanned regions (Table 4). Distance between patient centroid and gantry isocenter in the x-axis differed significantly (F = 12.394, $P < 0.0001$) as a function of scan region, with all comparisons significant except A vs CAP, P, C, AP; CAP vs P; P vs C; AP vs CA.

The majority of CT acquisitions (99.9% (57,561/57,621) were performed with the patient in the supine position as compared to the prone position (0.1% 60/57621). There was a significant difference (F = 119.411, $P < 0.0001$) in the distance between patient centroid and gantry isocenter in the y-axis as a function of patient position: supine mean = 1.7 cm below center (sd = 1.8); prone mean = 0.8 cm above isocenter (sd = 1.9). There was a significant difference (F = 26780.31, $P < 0.0001$) in the distance between patient centroid and gantry isocenter in the x-axis as a function of patient position: supine mean = 0.08 cm left of center (sd = 1.5); prone mean = 2.2 cm left of center (sd = 4.3).

Exams from CT machines with gantry apertures of 70 cm (n = 57, 201 exams) and 80 cm (n = 420 exams) were compared. Distance between patient centroid and gantry isocenter in the y-axis differed significantly (F = 69.502, $P < 0.0001$) as a function of gantry aperture, with 70 cm aperture mean = 1.7 cm (sd = 1.8) below isocenter and 80 cm aperture mean = 0.9 cm (sd = 2.2) below isocenter. Distance between patient centroid and gantry isocenter in the x-axis differed significantly (F = 117.71, $P < 0.0001$) as a function of gantry aperture with 70 cm aperture mean = 0.09 cm (sd = 1.5) to the left of isocenter and 80 cm aperture mean = 0.7 cm (sd = 3.3) to the right of isocenter.

A weak negative correlation was found for the distance between patient centroid and gantry isocenter in the y-axis and patient diameter ($r = -0.20$). No significant correlation was found for the distance between patient centroid and gantry isocenter in the x-axis and patient diameter ($r = 0.009$).

Discussion

The present evaluation of 57,621 adult CT acquisitions demonstrates the tendency of CT technologists, when centering patients based on visual estimate, to center patients such that their centroid is located below the isocenter of the CT gantry. This is in line with similar but much smaller studies (n = 63-549 patients),[8,9,14,15] that reported a mean off-centered distance of 2.2-2.3 cm below isocenter.[8,15]

The phantom study demonstrated that the patient centroid as computed by Radimetrics is not the same as the geometric center of the patient. Geometric center is an important variable, as magnification-related dose effects with automated tube current modulation are related predominantly to the geometric centering of the patient. Prior studies have found a direct relationship between vertical positioning of the subject closer to the x-ray source and subject magnification in the topogram.[12,16] The selection of maximum tube currents and tube voltages is then driven by the magnified size of the subject with use of topogram-based tube current modulation and tube voltage selection software.[12,16,17]

For example, in an anthropomorphic phantom study, Filev et al. found that when a phantom was off-centered 3 and 6 cm below isocenter, the phantom appeared 23% and 31% magnified in the topogram obtained with posterior-anterior technique with resultant selection of higher maximum tube currents and higher tube voltages (140 kV vs 120 kV) as compared to values selected with the patient in the centered position.[12] Prior human studies also have found a direct relationship between magnification in the

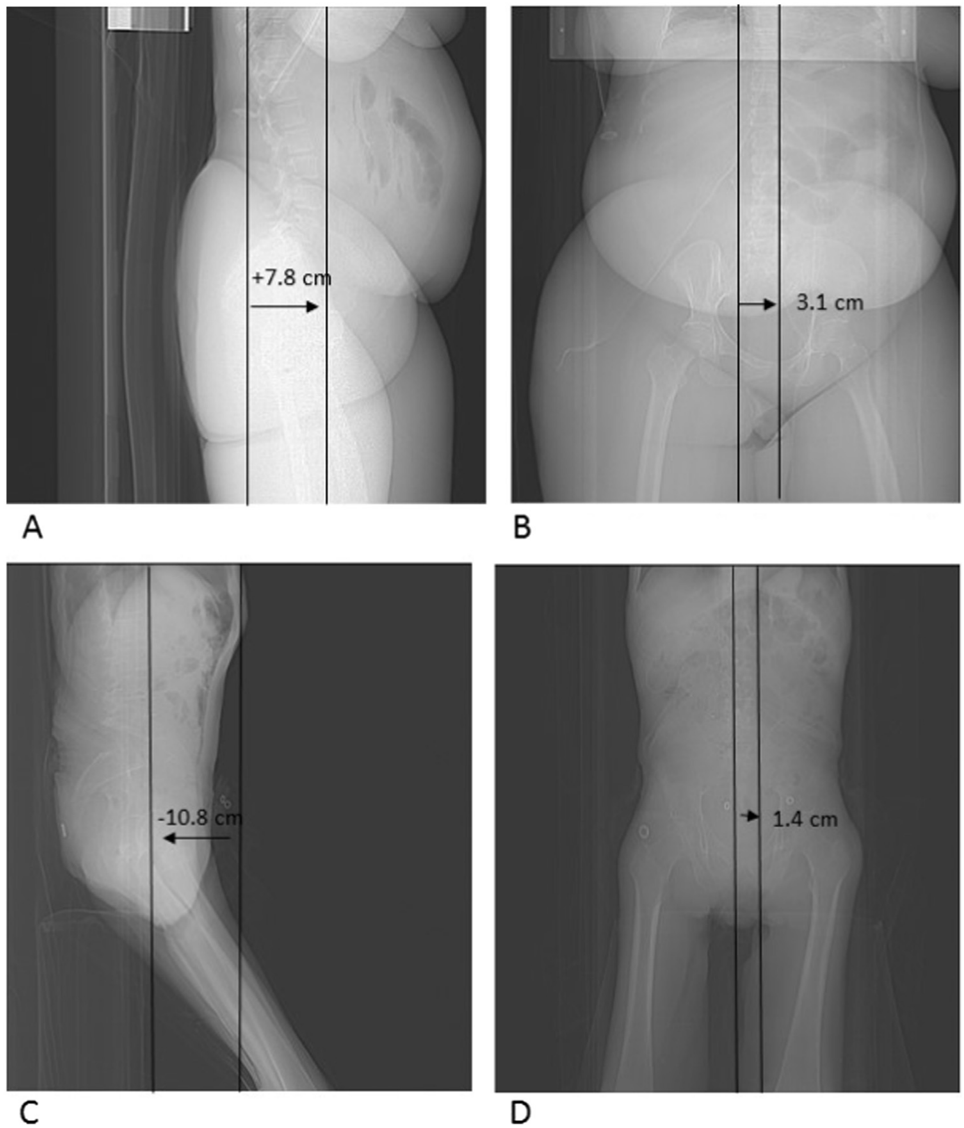

FIG 4. A 43-year-old woman with abdominal distention (A,B), and a 69-year-old man with renal cell carcinoma (C,D). (A,B) Lateral and frontal scout images performed as part of a CT examination. Distances between patient centroid and gantry isocenter: 7.8 cm above center (y-axis), 3.1 cm left of center (x-axis). (C,D) Lateral and frontal scout images performed as part of a CT examination. Distances between patient centroid and gantry isocenter: 10.8 cm below center (y-axis), 1.4 cm left of center (x-axis).

topogram and dose with use of topogram-based tube current modulation software.[11] Off-centering also impacts patient dose with use of bow-tie filters which shape the x-ray source and are designed to deliver more energy to more attenuating portions of the anatomy and less energy to the periphery of the patient.[8-10] In the phantom portion of this study, we found that dose also increased when the phantom was positioned closer to the x-ray source for the anterior-posterior topogram and image noise decreased.

TABLE 4
Mean patient centroid to gantry isocenter distances based on scanned region

Scan region	Mean (SD) centroid-to-isocenter-y* (cm)	Mean (SD) centroid-to-isocenter-x$^{\beta}$ (cm)
Chest	1.47 (1.7)	0.07 (1.5)
Chest, abdomen	1.89 (1.7)	0.21 (1.2)
Chest, abdomen, pelvis	1.89 (1.8)	–0.01 (1.2)
Abdomen	1.37 (1.6)	0.03 (1.2)
Abdomen, pelvis	1.82 (1.9)	0.13 (1.5)
Pelvis	1.89 (2.0)	–0.04 (3.6)

* All values are below isocenter.
$^{\beta}$ Positive numbers indicate a location left of center, negative numbers indicate a position right of center.

Off-centering in the x-axis was less severe, and a nearly equal number of patients were off-centered to the left of center versus to the right of center. Prior investigators also found off-centering in the x-axis to be less severe compared to y-axis off-centering. In a study of 549 patients, Toth et al. found lateral off-centering with a mean of 0.0 cm.[8] Gudjonsdottir et al. found minimal changes in mAs with horizontal off-centering.[17] Some authors advocate using a lateral topogram to determine tube current modulation.[22-24] Lateral topograms would be less subject to magnification effects as off-centering is less common in the x-axis. The optimal topogram technique may vary based on vendor implementation of automated tube current modulation and voltage selection software and the relative contribution of information from the topogram.

In the present study, 21.3% of patients were positioned such that their centroid was located between 3 and 6 cm above or below the isocenter, and 1.5% of patients were positioned with centroid > 6 cm above or below the isocenter. Previous investigators found that surface and peripheral CTDI dose increased 12%-18% with a 30-mm off-center distance and increased 41%-49% with a 60 mm off center distance, and this increase was attributed to malpositioning with respect to the morphology of the x-ray beam due to the beam shaping qualities of a bow-tie filter.[9] Habibzadeh et al. found maximum surface dose increases of 13.5%, 33.3%, and 51.5% when a phantom was off-centered by 2, 4, and 6 cm, respectively, due to bow-tie filter effects.[15] In a study of a pediatric anthropomorphic phantom, breast dose increased up to 16% and thyroid dose increased up to 24% with off-centering.[18]

It is not always possible to center a patient in the isocenter of the CT gantry. Some patients may have physical or other limitations that prevent their being optimally centered in the isocenter of the CT gantry. For example, patients with shoulder derangement may be unable to place their arms behind their heads when undergoing chest CT which limits elevation of the CT table due to contact with the CT gantry and may result in suboptimal positioning. Additionally, the patient's centroid changes over the z-axis of the patient which makes positioning based on visual estimate challenging.

The current investigation has some limitations. The version of Radimetrics used in this study computed distance between patient centroid and gantry isocenter. Software capable of computing the distance between the patient's geometric center and the isocenter of the CT machine would be useful to assess the accuracy of patient centering with respect to topogram magnification effects. Prior investigations of the impact of miscentering on dose with use of a bow-tie filter investigated primarily cylindrical phantoms. The relationship of bow-tie filter effects to geometric center versus centroid off-centering is not well established. Additionally, this project was a retrospective review of a large database, and we cannot exclude the possibility of errors in data entry at the time each patient was scanned (eg, scan position). An additional limitation is that we could not directly determine the impact of off-centering on patient dose. Owing to variability of equipment, implementations of tube current modulation and other scan parameters, and the large number of scanning protocols used, we could not directly determine dose implications of off-centering in this study.

Conclusions

In summary, in the largest series published to date, we have documented the tendency of CT technologists to center patients' centroids below the isocenter in the CT gantry when centering is performed based on visual estimate. Further investigation of the prevalence and severity of geometric off-centering is needed as geometric off-centering has implications for patient dose based on topogram magnification effects with use of topogram-based tube current modulation and tube voltage selection software.

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