POINT ORGAN RADIATION DOSE IN ABDOMINAL CT: EFFECT OF PATIENT OFF-CENTERING IN AN EXPERIMENTAL HUMAN CADAVER STUDY

Ranish Deedar Ali Khawaja^{1,*}, Sarabjeet Singh¹, Atul Padole¹, Alexj Otrakji¹, Diego Lira¹, Da Zhang¹, Bob Liu¹, Andrew Primak², George Xu³ and Mannudeep K. Kalra¹

¹MGH Imaging, Massachusetts General Hospital, Fruit St, Boston, MA 02114, USA

²Siemens Healthcare USA, Malvern, PA, USA

³Rensselaer Polytechnic Institute, Troy, NY, USA

*Corresponding author: ranish.khawaja@duke.edu

Received 21 October 2016; revised 25 November 2016; accepted 2 December 2016

To determine the effect of patient off-centering on point organ radiation dose measurements in a human cadaver scanned with routine abdominal CT protocol. A human cadaver (88 years, body-mass-index 20 kg/m²) was scanned with routine abdominal CT protocol on 128-slice dual source MDCT (Definition Flash, Siemens). A total of 18 scans were performed using two scan protocols (a) 120 kV–200 mAs fixed-mA ($CTDI_{vol}$ 14 mGy) (b) 120 kV–125 ref mAs (7 mGy) with automatic exposure control (AEC, CareDose 4D) at three different positions (a) gantry isocenter, (b) upward off-centering and (c) downward off-centering. Scanning was repeated three times at each position. Six thimble (in liver, stomach, kidney, pancreas, colon and urinary bladder) and four MOSFET dosimeters (on cornea, thyroid, testicle and breast) were placed for calculation of measured point organ doses. Organ dose estimations were retrieved from dose-tracking software (eXposure, Radimetrics). Statistical analysis was performed using analysis of variance. There was a significant difference between the trends of point organ doses with AEC and fixed-mA at all three positions ($p < 0.01$). Variation in point doses between fixed-mA and AEC protocols were statistically significant across all organs at all Table positions ($p < 0.001$). There was up to 5–6% decrease in point doses with upward off-centering and in downward off-centering. There were statistical significant differences in point doses from dosimeters and dose-tracking software (mean difference for internal organs, 5–36% for fixed-mA & 7–48% for AEC protocols; $p < 0.001$; mean difference for surface organs, >92% for both protocols; $p < 0.0001$). For both protocols, the highest mean difference in point doses was found for stomach and lowest for colon. Measured absorbed point doses in abdominal CT vary with patient-centering in the gantry isocenter. Due to lack of consideration of patient positioning in the dose estimation on automatic software—over estimation of the doses up to 92% was reported.

INTRODUCTION

CT radiation dose has been associated with radiation-induced risks such as cancers^(1, 2). Many patient and scanner related factors affect CT radiation dose such as patient size (body weight, body-mass-index, effective diameter), scan parameters (tube voltage, tube current, pitch factor, collimation, automated exposure control [AEC]), software technology (iterative reconstruction techniques) and hardware technology (helical CT scanner versus non-helical)^(3–6). Patient-centering in CT gantry is an important technical factor affecting CT radiation doses^(7, 8). Inappropriate positioning of the patient in the gantry isocenter affects the CT dose as well as image quality⁽⁸⁾.

The cross-section for average or small patient is elliptical with thicker center (which requires higher radiation due to greater beam attenuation) as compared to its thinner periphery (which may be imaged at lower dose due to lower beam attenuation)⁽⁷⁾. Bow-tie filters help to ‘shape’ X-ray beam attenuation profile across the cross-section of patient’s body at the

time of scan⁽⁹⁾. These filters have shown to work most effectively when patient is optimally centered in the CT gantry (also referred to iso-centered)^(10, 11). With inappropriate centering or off-centering, there is an inappropriate compensation of beam attenuation by bow-tie filters. This in turn alters the radiation dose across patient body surface⁽⁹⁾. However, to our best knowledge, the effect of patient off-centering on individual internal and surface body organs has not been assessed in a human body.

The purpose of our study was to determine the effect of off-centering on point organ radiation dose measurements with an experimental study using a human cadaver scanned with routine abdominal CT protocol.

MATERIALS AND METHODS

Financial disclosure

S.S. received research funding from the Radiological Society of North America (RSNA), GE Healthcare,

Philips Healthcare and Toshiba American Systems. M.K.K. has received RSNA Educational Scholar Grant. The remaining authors have no financial disclosures and had full control of study data during the study.

Cadaver acquisition and demographics

The requirement of institutional review board approval was waived by our Human Research Committee. We obtained a male human cadaver (age: 88 years, body weight: 68 kg, height: 183 cm, anteroposterior diameter: 33 cm, lateral diameter: 20 cm, body-mass index: 20 kg/m²) from an accredited and approved not-for-profit entity Science Care Inc. (Phoenix, AZ). The body was shipped in a frozen state and thawed for three days before the day of the experiment. After the experiment (performed within two weeks from the date of death), the body was sent back to Science Care for regulatory disposal.

Dosimeters

Two different types of dosimeters were used in this dosimetry experiment, (a) Thimble ionization chambers (Model $\times 105-0.6$ CT and $\times 106-0.6$ CT, Radcal Inc., California) were used for point dose measurements in the internal body organs, and (b) metal-oxide semiconductor field-effect transistor (MOSFET) dosimeters were used for point dose measurements on the surface body parts. Both models of thimble chambers were similar in their design but had a different interface to connect to dose monitors. We used six thimble chambers for a set of six different internal body organs to measure absorbed organ doses at the point of dosimeter placement. All dosimeters were set to baseline zero before any additional acquisitions were scanned. The MOSFET dosimeters have been validated in prior studies for CT dose measurements and have shown to be sensitive to very small doses of radiation^(12, 13). All six dosimeters were calibrated and their response was verified as 'insensitive' to the beam quality and reproducible with coefficients of variance within 0.5%. The details for the dosimeter calibration have been described in the prior literature⁽¹⁴⁾.

Dosimeter placement

Four of the co-authors (D.L., M.K.K., S.S. and A.O.) performed the following surgical procedure for the placement of dosimeters that took place in the autopsy procedure room at the morgue of our hospital. Midline vertical and horizontal incisions were made in the anterior abdominal wall from xiphoid process to the pubic symphysis pubis. Six dosimeters were placed in six different locations that included liver, stomach, kidney (left-sided), pancreas, ascending colon and

urinary bladder. All dosimeters were placed inside the organs as shown in Figure 1. Prior to their placement in the body, the chambers were protected from the body fluids with thin rubber sheaths covering the entire thimble dosimeters. The dosimeters were retained in constant position in the body with purse-string suture and surgical-glove.

MOSFET dosimeters (EDD-30 Unfors Instrumentals, Billdal, Sweden) were deployed on the skin surface for the following four body parts: cornea (left-sided, representing point surface dose to lens), hyoid bone (left-sided, representing point surface dose to thyroid), nipple (right-sided, representing point surface dose to breast) and scrotum (left-sided, representing point surface dose to testicle). The dosimeters were taped to the skin surface to avoid displacement and maintain a constant position throughout the entire study.

Scanning technique and dose measurements

Scanning technique of the dose experiment along with protocols and scan parameters are summarized in Table 1. The body was scanned using routine abdominopelvic CT protocol on a 128-slice dual source CT (Definition Flash, Siemens Healthcare, Germany). CT examinations were based on two scan protocols⁽¹⁾: Protocol A: 120 kVp with fixed mA ($CTDI_{vol}$ 14 mGy; 'volumetric computed tomographic dose index') and⁽²⁾ Protocol B: 120 kVp with both in-plane (xy) and longitudinal (z) AEC with CareDOSE 4D enabled (7 mGy). Other scan parameters such as kVp (120), collimation 128 $\times$ 0.6 mm² with z-flying focal spot and pitch factor of

Figure 1. (A) Localizer radiograph showing the placement of six dosimeters inside the abdomen and pelvis region of the cadaver. (B) Dissection of cadaver for insertion of Thimble dosimeters (yellow arrows point towards wires coming off from Thimble dosimeters).

Table 1. Scanning technique: protocols and parameters.

Scan	Table height (mm)	Serial number	mAs	$CTDI_{vol}$ (mGy)	DLP (mGy*cm)	SSDE (mGy)
<i>Protocol A. Fixed tube current</i>						
Position A: Optimal centering	114	Scan 1	180	14	744	20
		Scan 2	“	“	“	“
		Scan 3	“	“	“	“
Position B: Positive off-centering	104	Scan 1	“	“	“	“
		Scan 2	“	“	“	“
		Scan 3	“	“	“	“
Position C: Negative off- centering	154	Scan 1	“	“	“	“
		Scan 2	“	“	“	“
		Scan 3	“	“	“	“
<i>Protocol B. AEC</i>						
Position A: Optimal centering	114	Scan 1	105.5	7	401	11
		Scan 2	96.9	“	401	“
		Scan 3	97.4	“	403	“
Position B: Positive off-centering	104	Scan 1	97.3	“	403	“
		Scan 2	97.2	“	403	“
		Scan 3	97.1	“	403	“
Position C: Negative off- centering	154	Scan 1	95.4	“	397	“
		Scan 2	95.3	“	397	“
		Scan 3	95.0	“	395	“

*Other scan parameters were kept constant at pitch 0.9, 120 kV, collimation $\times 1280.6$, rotation time 0.5 s, and slice thickness 5 mm.

“Represents same value as above.

(0.9) were kept constant for both protocols. The scan-length was kept constant and extended from the dome of diaphragm to pubic symphysis.

To quantify the effect of inappropriate centering in the gantry isocenter on radiation dose, the cadaver was positioned in the gantry isocenter with orthogonal centers of the body aligned to the center of the gantry. Scans were performed at three different positions (Figure 2): (1) *Table Position A*: optimal centering (isocenter), 0 mm from CT gantry isocenter (measured height, 114 mm); (2) *Table Position B*: off-centering, 10 mm above the CT gantry (measured height, 104 mm); and (3) *Table Position C*: off-centering, 40 mm below the CT gantry (measured height, 154 mm). For each position and technique (fixed mAs and AEC), scanning was repeated three times. First, the cadaver was centered in the gantry isocenter. Fixed mAs technique was applied and scanning was repeated three times. Then AEC was applied and scanning was repeated three times. This exercise was repeated for positions B and C (Table 1). For each scan acquisition in the gantry, absorbed radiation dose was recorded for internal and surface organs with thimble and skin dosimeters, respectively.

We acquired two orthogonal localizer radiographs for planning CT acquisitions for all three positions (A, B and C). Scanning was then performed according to the usual department protocol for abdominal

Figure 2. Diagram showing the three scanning positions for the cadaver (A, optimal centering; B, upward off-centering; C, downward off-centering relative to iso). Gray circle (position B) was moved upwards at the distance of 10 mm to reach position A (red circle) and moved downwards at the distance of 40 mm to reach position C (blue circle).

CT examination with both in-plane (xy) and longitudinal (z)-axis modulation (CareDose 4D, Siemens Healthcare). Subsequently, we applied fixed mAs for scanning at each position.

After each scan acquisition, doses were recorded independently by four co-investigators (R.D.A.K., A.P., S.S. and A.O.) from thimble and skin dosimeters. Each measurement was recorded twice. The measurements were cross-checked at the end of the scanning to correct any inadvertent human errors within measurements. Measured doses (Roentgen for thimble dosimeters, and milliRoentgen for skin dosimeters) were converted to milliGrays (mGy).

Automated dose measurements

A web-based dose-monitoring software (eXposure, Radimetrics Inc., Toronto) was used to also estimate individual organ doses for each acquired series by exporting all the series to the software. We compared the software estimated organ doses with our dosimeter measurements described above.

Dosimeter placement in x - y plane

To determine the relative position of each dosimeter with respect to the gantry isocenter, we used a grid function on a standard diagnostic image workstation (Philips EBW, Cleveland, OH). The x, y coordinates of each dosimeter were measured with respect to the gantry isocenter since 0,0 coordinate represent the center of the grid. We measured positions of the tips of the internal organ dosimeters in order to assess the relationship between variations in organ doses with changes in the position of the Thimble dosimeters with respect to the CT gantry isocenter. The placement of dosimeters in an axial plane has been shown in Figure 3.

Objective image quality

In order to assess the change in image quality with patient off-centering in our experiment, we measured image noise measurements. Measurements (including CT attenuation and standard deviation) were made along a homogenous area in liver parenchyma, urinary bladder, abdominal fat and right psoas muscle. All measurements were performed using a region of interest (ROI) with a size of 20 mm^2 on standard diagnostic workstation.

Statistical analysis

Data were compiled and descriptive analysis was performed on spreadsheet on Microsoft Excel version 2003 (Richmond, VA). All statistical analysis was performed with Statistical Package for Social Sciences version 18.0 (SPSS, IBM, Chicago, IL). One-way analysis of variance (ANOVA) was performed to measure statistical differences across dose measurements: (a) overall organ doses across fixed-tube mA protocol, and across three position levels (b), organ doses across AEC protocol, and across

Figure 3. Demonstration of the thimble dosimeters into internal organs on the axial CT images (key: a, liver; b, kidney; c, colon; d, pancreas; e, stomach; f, urinary bladder).

three position levels (c), *in vitro* organ doses versus estimated organ doses. A value of $p < 0.05$ (two-sided) was the criterion for statistical significance. A post-hoc test (Bonferroni's Multiple Comparison test) was performed in cases where statistical significance was found. Paired- t test was performed for comparison of repeated organ dose measurements for organs across two different scan protocols (fixed mAs versus AEC). p Value of 0.05 or less (two-sided) was considered statistically significant.

RESULTS

Radiation dose

Overall radiation dose ($CTDI_{vol}$) with AEC scan protocol was significantly lower than fixed-mAs protocol (7 mGy versus 14 mGy). Table 1 shows radiation dose descriptors ($CTDI_{vol}$, DLP 'dose-length product' and SSDE 'size-specific dose estimate') for both protocols. Individual organ doses (in mGy) across both scan protocols have been tabulated in Table 2. Table 3 summarizes change in position of the internal organ dosimeters with respect to the CT gantry isocenter in an x - y plane.

Dose measurements for internal organs

Fixed tube current

Point dose in urinary bladder received the highest and kidney received the lowest overall dose irrespective of body positioning in the gantry isocenter ($p < 0.001$;

Table 2. Measured organ doses (in milliGray, mGy) with Thimble dosimeters for protocol A (fixed tube current, 120 kV, 200 mAs, $CTDI_{vol}$ 14 mGy) and protocol B (AEC, 120 kV, 125 ref mAs, $CTDI_{vol}$ 7 mGy).

Organs	Position A (optimally centered)			Position B (off-centered)			Position C (off-centered)		
<i>Protocol A: fixed tube current</i>									
Stomach	16.7	16.5	17.2	16.9	16.6	16.5	18.1	17.1	17.1
Liver	21.8*	22.5*	22.4*	21.8*	21.6*	21.5*	22.9*	22.3*	22.4*
Kidney	20.2	19.9	20.1	19.8	19.8	19.7	20.3	19.9	20.1
Pancreas	16.5	17.3	17.1	16.7	16.5	16.3	16.97	16.83	16.74
Colon	21.83	21.75	21.68	21.48	21.52	21.65	21.66	21.7	21.68
Urinary bladder	24*	24.82*	24.1*	23.06*	22.83*	23.47*	25.91*	26.19*	25.57*
<i>Protocol B: AEC</i>									
Stomach	8.017	7.496	7.383	7.2	7.217	7.191	7.443	7.53	7.348
Liver	9.635	9.638	9.687	9.426	9.574	9.513	9.487	9.591	9.409
Kidney	10.92	10.83	10.99	11.89	10.71	10.66	10.55	10.17	10.37
Pancreas	8.287	8.035	7.904	7.539	8.539	7.861	8.017	7.826	7.322
Colon	11.79	11.59	12.02	11.38	11.5	11.23	11.07	11.13	11.14
Urinary bladder	11.87*	11.9*	11.47*	11.14*	11.07*	11.07*	14.59*	14.58*	14.17*

*Statistically significant with ANOVA analysis $p < 0.01$.

Table 3. x and y coordinates for the position of internal organ dosimeters in an x - y plane. The distance from the CT iso-gantry is given in millimeters (mm).

Organs	Position A (Optimal centering)			Position B (Off-centering)			Position C (Off-centering)		
Stomach	(70.7, 36.0) ^a			(75.3, 46)			(73.2, 8.0)		
Liver	(−65.0, 45.5)			(−64.0, 55.8)			(−64.5, 6.4)		
Kidney	(94.8, 11.6)			(94.3, 20.8)			(94.3, -28.0)		
Colon	(−115.4, 29.0)			(−115.9, 39.3)			(−117.4, 12.1)		
Pancreas	(76.8, 27.5)			(76.3, 37.8)			(76.8, 12.6)		
Urinary bladder	(7.5, 61.4)			(7.5, 71.7)			(7.5, 21.8)		
Organs	Position A (optimally centered)			Position B (off-centered)			Position C (off-centered)		
<i>Protocol A: fixed tube current</i>									
Left eye	0.00057	0.0006187	0.0006352	0.0006096	0.0006319	0.0006026	0.0006108	0.0006405	0.000671
Thyroid gland	0.003729	0.003725	0.003749	0.003685	0.003671	0.003621	0.003928	0.003921	0.003924
Left nipple	0.1144*	0.1092*	0.1113*	0.1102*	0.1129*	0.08495*	0.1223*	0.1314*	0.1291*
Testicle	0.02768*	0.02791*	0.02798*	0.02754*	0.02752*	0.02737*	0.02797*	0.02789*	0.02794*
<i>Protocol B: tube current modulation</i>									
Left eye	0.0003807	0.0003736	0.0004071	0.0003463	0.0003412	0.0003909	0.0004007	0.0003878	0.000417
Thyroid gland	0.001832	0.001751	0.001832	0.001731	0.001768	0.001782	0.001852	0.001839	0.001846
Left nipple	0.04456*	0.04275*	0.05782*	0.0287*	0.0341*	0.02932*	0.05017*	0.0507*	0.05714*
Testicle	0.01506	0.01325	0.01305	0.01277	0.01279	0.01286	0.01364	0.01364	0.01344

^a(x , y) = first value represent position of dosimeter on x -axis and second value represent position of dosimeter on y -axis.

Measured surface doses (in milliGray, mGy) for surface organs as measured by MOSFET dosimeters for protocol A (fixed tube current, 120 kV, 200 mAs, $CTDI_{vol}$ 14 mGy) and protocol B (AEC, 120 kV, 125 ref mAs, $CTDI_{vol}$ 7 mGy).

*Statistically significant with ANOVA analysis $p < 0.05$.

Figure 3 and Table 2). Radiation doses were not affected with the change in body positioning for stomach, kidney and pancreas ($p = 0.14$, $p = 0.21$ and $p = 0.08$, respectively). Point dose in liver significantly increased with negative off-centering (position C), and significantly decreased with positive off-centering

(position B) compared to optimal centering (position A; 23 ± 0.3 mGy and 22 ± 0.2 mGy, respectively; $p = 0.027$). However, the variation was only less than 5%. Dose to ascending colon was significantly higher at position A and significantly lower at position B compared to position C (22 ± 0.1 mGy and 21 ± 0.1 mGy,

respectively; $p = 0.032$). With post-hoc analysis, dose was significantly lower with position B only ($p < 0.05$). Radiation dose to urinary bladder was significantly different across all three positions ($p = 0.0003$).

AEC

Ascending colon received the highest and stomach received the lowest overall dose ($P < 0.001$; Figure 4 and Table 2). Radiation doses were not affected with the change in body positioning for stomach, liver, kidney and paravertebral gutter ($p = 0.23$, $p = 0.057$, $p = 0.53$ and $p = 0.17$, respectively). Radiation dose to ascending colon was significantly different across three positions ($p = 0.0034$). On post-hoc analysis, dose was significantly increased at position A compared to positions B and C ($p < 0.05$ and $p < 0.01$, respectively). Radiation dose to urinary bladder was significantly different across different positions ($p < 0.0001$). Dose was significantly increased at position C ($p < 0.05$) and significantly decreased at position B ($p < 0.0001$) compared to neutral position A (14 ± 0.23 mGy and 11 ± 0.04 mGy, respectively).

Mean doses for internal organs were significantly lower for scan protocol B compared to scan protocol A across all internal organs at all three different positions.

Dose measurements for surface organ doses

Fixed tube current

Nipple received the highest and cornea received the lowest measured point doses irrespective of body positioning ($p < 0.001$; Table 3 and Figure 4). Radiation doses were not affected with the change in body positioning for breast, cornea and thyroid gland (both $p = 0.37$). Radiation dose to testicle was significantly different across three positions ($p = 0.005$).

AEC

Nipple received the highest and cornea received the lowest overall dose ($p < 0.001$; Table 3 and Figure 4). Radiation doses were not affected with the

Figure 4. Trends of point organ doses across fixed-mA and automatic exposure control (AEC) enabled CT protocols with off-centering.

change in body positioning for cornea, thyroid gland and testicle (all $p = 0.11$). Radiation dose to nipple was significantly different across three positions ($p = 0.0062$).

Mean doses for internal organs were significantly lower for scan protocol B compared to scan protocol A across all internal organs at all three different positions.

Correlation between experimental and automated measurements

Tables 4 and 5 reports individual organ doses (internal and surface) estimated with automatic dose-tracking software. Table 6 reports the mean percentage (%) difference between measured organ doses and software estimated values.

Table 4. Averaged absorbed doses (in milliGray, mGy) for internal organs as estimated by automatic software for protocol A (fixed tube current, 120 kV, 200 mAs, $CTDI_{vol}$ 14 mGy) and protocol B (AEC, 120 kV, 125 ref mAs, $CTDI_{vol}$ 7 mGy).

Organs	Optimally centered	Off-centered	Off-centered
<i>Protocol A</i>			
Stomach	26	26	26
Liver	25	25	25
Kidneys	27	27	27
Upper large intestine	23	23	23
Urinary bladder	16	21	24
<i>Protocol B</i>			
Stomach	14	14	14
Liver	13	14	13
Kidneys	14	14	14
Upper large intestine	13	13	12
Urinary bladder	13	13	13

*Statistically significant with ANOVA analysis $p < 0.001$

Objective noise measurements (CT attenuation and standard deviation) did not change significantly across optimally centered and off-centering positions ($p > 0.05$) for all ROIs (liver, urinary bladder, abdominal fat and muscle).

DISCUSSION

Our dose experiment highlighted the importance of patient centering technique by demonstrating variable effects on certain organ point radiation dose measurements in routine abdominopelvic CT. Measured point organ doses (for urinary bladder and testicle) were significantly lower with positive off-centering of patient from the CT gantry with a fixed mAs protocol ($p < 0.05$). For the same protocol, dose measurements (for urinary bladder and testicle) were significantly higher with negative off-centering ($p < 0.01$). For AEC protocol, point dose measurements for urinary bladder were significantly lower with positive off-centering ($p < 0.05$), and significantly higher with negative off-centering ($p < 0.01$). Hence, the organs on or near the surface showed significant changes in point dose measurements with regard to off-centering. Whereas, internal organs did not show much variability with regard to off-centering.

We observed no significant effects on dose measurements for breast, cornea and thyroid gland (among surface organs) and stomach, kidney, and pancreas (among internal organs). On the contrary, the dose measurements for testicle varied significantly for fixed mAs protocol. Although variations in dose measurements were seen in both stomach and liver, we do not understand why only liver (and not stomach) had statistically significant variations with different off-centering positions. Additionally, significant variation in liver dose was seen in fixed tube current protocol only. We believe this may be due to the influence of tube starting angle.

There were significant differences in the measured point doses in liver and urinary bladders with

Table 5. Individual organ doses (in milliGray, mGy) for surface organs as estimated by automatic software for protocol A (fixed tube current, 120 kV, 200 mAs, $CTDI_{vol}$ 14 mGy) and protocol B (AEC, 120 kV, ref 125 mAs, $CTDI_{vol}$ 7 mGy).

Organs	Optimally centered				Off-centered		Off-centered		
<i>Scan A</i>									
Left eye	0.06	0.06	0.06	0.17	0.06	0.06	0.11	0.14	0.06
Thyroid gland	1.48	1.48	1.48	14.70	1.48	1.48	2.78	3.70	1.48
Left nipple	23.00	23.00	23.00	23.00	23.00	23.00	23.00	23.00	23.00
<i>Scan B</i>									
Left eye	0.02	0.03	0.03	0.12	0.03	0.03	0.03	0.03	0.03
Thyroid gland	1.85	0.80	0.79	0.79	0.80	0.79	0.80	0.80	0.78
Left nipple	10.67	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00

*Statistically significant with ANOVA analysis $p < 0.001$

Table 6. Mean percentage (%) difference for point dose measurements based on cadaver experiment and estimated doses derived from dose-tracking software.

Organs	Centered		Off-centered		Off-centered	
	Mean % difference ^a	<i>p</i> -Value	Mean % difference	<i>p</i> -Value	Mean % difference	<i>p</i> -Value
<i>Protocol A</i>						
Stomach	35.4%	0.0005	35.8%	0.0034	33.0%	0.0016
Liver	11.1%	0.0067	13.5%	0.0009	9.7%	0.0065
Left kidney	37.3%	0.0006	38.9%	0.0001	37.6%	0.0006
Colon	5.4%	0.112	6.3%	0.0013	5.7%	0.112
Urinary bladder	1.2%	0.2784	3.8%	0.5568	7.3%	0.0089
<i>Protocol B</i>						
Stomach	45.4%	0.0009	48.5%	0.0018	46.8%	0.01
Liver	25.7%	0.0073	32.1%	<0.0001	26.9%	0.0002
Left kidney	42.3%	0.0004	43.0%	0.0024	44.8%	0.0011
Colon	9.2%	0.0105	12.5%	0.0023	7.3%	0.0006
Urinary bladder	16.0%	0.0337	14.6%	0.0001	10.0%	0.0118

^aMean % difference was calculated as: (mean dose for scan protocol A—mean dose for scan protocol B) divided by mean dose for scan protocol A.

off-centering but no such differences were found for other internal organs (pancreas, left kidney, stomach and colon) ($p < 0.01$). As noted in Table 3, liver and urinary bladder were closer to the CT isocenter (in both x and y axes) as compared to the other organs. The bow-tie or beam shaping filters allow more x-rays to ‘pass through’ for trajectory closest to the gantry isocenter as compared to the periphery resulting in more pronounced variations in liver and urinary bladder doses as they move from closer to the CT isocenter to the periphery of the scan field of view. On the other hand, least variations in measured point doses were noted from dosimeter placed in the colon due to the fact that it was positioned in the most peripheral portion of the body in relation to the gantry isocenter (−115 versus −65 to 95 range for other organs).

Dose measurements for urinary bladder showed a consistent pattern of variability across both scan protocols. Dose was significantly lower with positive off-centering and higher with negative off-centering from CT gantry ($p < 0.05$). We believe such consistent findings may be due to most superficial location of bladder among all assessed organs in the scanned body region. Additionally, no significant changes were noted in the objective image noise across off-centering positions compared to optimal centering position in our study. This may be due to limited off-centering performed on human cadaver.

Habibzadeh *et al.*⁽¹⁵⁾ studied the impact of miscentering in both clinical and phantom settings. They reported an average increase (13–51%) for surface radiation dose with off-centering from isocenter⁽¹⁵⁾. These findings are consistent with our study. Additionally, we provide additional insight for

individual organs that surface organs (such as urinary bladder and testicles) demonstrated significant variation in point measured doses. Kaasalainen *et al.*⁽¹⁶⁾ recently evaluated the effect of vertical centering on dose and image noise using both clinical and phantom data. They reported up to 12–38% increased dose with the lowest Table position and up to 8–23% decreased dose with the highest Table position⁽¹⁶⁾.

Gudjonsdottir *et al.*⁽¹⁷⁾ studied the effects of patient off-centering (at 30-mm intervals) on the tube current–time product (mAs) and image noise on an oval-acrylic phantom scanned in three different CT scanners. They demonstrated that patient off-centering affects the efficacy of AEC function, and the changes in tube current are variable across the scanners. The errors in tube current modulation caused by off-centering damages the image quality of CT images as well as increases radiation dose. Li *et al.* studied the effect of an automatic patient-centering technique on radiation dose with a 32-cm CTDI phantom and patient imaging undergoing chest or abdominal CT with AEC enabled. The change in CTDI ranged from 12–18% (with 30-mm off-centering) and 41–49% (with 60-mm off-centering). The mean dose that was saved with the use of automatic technique ranged from 3 to 30%⁽⁹⁾.

Li *et al.* determined the effect of an automatic patient-centering technique (a laser-guided prototype developed by one of the vendors) on radiation doses associated with MDCT in phantom and patients. They reported a substantial increase in peripheral and surface CTDIs in the phantom with off-centering (up to 18% increase with 30-mm and up to 49% with 60-mm off-center distance, respectively),

with a substantial increase in noise⁽⁹⁾. This finding correlates well with our study results in that point dose measurements at surface organs (such as testis and nipple) increased up to 27% with 40-mm off-centering. Additionally, doses for internal organs (such as liver and urinary bladder) increased up to 6% with 40-mm of centering. These changes are most likely the result of aforementioned description of bow-tie filters⁽¹⁰⁾. According to the group, there was a dose saving of up to 30% for chest CT and up to 56% for abdominal CT with automatic centering technique⁽⁹⁾. Hence, that highlights the role such techniques in organ dose conservation in clinical CT examinations^(9, 18).

Kaasalainen *et al.*⁽¹⁹⁾ studied effect of positioning on organ doses in pediatric chest CT examinations. They reported that vertical off-centering of the patient markedly affects organ dose distribution in addition to image noise and image quality. Patient off-centering below the isocenter of the scanner causes increased surface doses to anterior radiosensitive organs. While the posterior organs received increased doses when off-centered above the isocenter. The radiologic technologists can save radiation doses for their patients with proper centering within the CT gantry. Scanner gantries have laser beams that should be used by technologists to center the patient in the isocenter of the scanner gantry. An automatic centering technique may prove useful in reducing organ radiation dose and improving image quality⁽²⁰⁾.

Our study has the following major implications. Firstly, patient centering technique affects organ radiation dose measurements in abdominopelvic CT. However, the effect is variable depending on the position of the organ in the body and extent of off-centering from CT gantry. Secondly, point dose measurements are position dependent. That is, organs located in the surface are more likely to get affected with off-centering than internal organs.

Our experiment has several limitations. Most importantly, the positions (B and C) were not equally off-centered (one was 10 mm above, and the other was 40 mm below the neutral position at CT gantry). During the scanning part of experiment, we could not bring the CT Table beyond 10 mm above the isocenter. However, even with this small magnitude of off-centering in this direction, we found statistically lower dose measurements compared to optimal centering. Another limitation of the experiment was that recording of dose measurements were only performed thrice to assess the fluctuation in dose measurements. More repeated measurements would have further strengthened the accuracy for our experimental findings. Due to our limited resources, only six thimble dosimeters were available that restricted our list of target organs for this experiment. Finally, tube starting angle was not considered in our experiment.

Measured absorbed point doses (especially for surface organs such as urinary bladder and testicle) in abdominal MDCT vary with patient centering in the gantry isocenter. Due to lack of consideration of patient positioning in the dose estimation on automatic software—over estimation of the doses up to 92% was reported.

FUNDING

This research is sponsored in part by the National Institute of Biomedical Imaging and Bioengineering (R01EB015478).

REFERENCES

1. Miglioretti, D. L. *et al.* *The use of computed tomography in pediatrics and the associated radiation exposure and estimated cancer risk.* JAMA Pediatr. **167**(8), 700–707 (2013).
2. Brenner, D. J. and Hall, E. J. *Computed tomography—an increasing source of radiation exposure.* N. Engl. J. Med. **357**(22), 2277–2284 (2007).
3. Kalra, M. K., Maher, M. M., Toth, T. L., Hamberg, L. M., Blake, M. A., Shepard, J. A. and Saini, S. *Strategies for CT radiation dose optimization.* Radiology **230**, 619–628 (2004).
4. Khawaja, R. D. *et al.* *Computed tomography (CT) of the chest at less than 1 mSv: an ongoing prospective clinical trial of chest CT at Submillisievert radiation doses with Iterative Model Image Reconstruction and iDose4 Technique.* J. Comput. Assist. Tomogr. **38**(4), 613–619 (2014).
5. Khawaja, R. D., Singh, S., Lira, D., Bippus, R., Do, S., Padole, A., Pourjabbar, S., Koehler, T., Shepard, J. A. and Kalra, M. K. *Role of compressive sensing technique in dose reduction for chest computed tomography: a prospective blinded clinical study.* J. Comput. Assist. Tomogr. **38**(5), 760–767 (2014).
6. Khawaja, R. D., Singh, S., Madan, R., Sharma, A., Padole, A., Pourjabbar, S., Digumarthy, S., Shepard, J. A. and Kalra, M. K. *Ultra low-dose chest CT using filtered back projection: comparison of 80-, 100- and 120kVp protocols in a prospective randomized study.* Eur. J. Radiol. **83**(10), 1934–1944 (2014).
7. Kalra, M. K., Dang, P., Singh, S., Saini, S. and Shepard, J. A. *In-plane shielding for CT: effect of off-centering, automatic exposure control and shield-to-surface distance.* Korean J. Radiol. **10**(2), 156–163 (2009).
8. Kalra, M. K., Maher, M. M., Kamath, R. S., Horiuchi, T., Toth, T. L., Halpern, E. F. and Saini, S. *Sixteen-detector row CT of abdomen and pelvis: study for optimization of z-axis modulation technique performed in 153 patients.* Radiology **233**, 241–249 (2004).
9. Li, J., Udayasankar, U. K., Toth, T. L., Seamans, J., Small, W. C. and Kalra, M. K. *Automatic patient centering for MDCT: effect on radiation dose.* Am. J. Roentgenol. **188**(2), 547–552 (2007).
10. Avilés Lucas, P., Castellano, I. A., Dance, D. R. and Vañó Carruana, E. *Analysis of surface dose variation in*

- CT procedures. Br. J. Radiol. **74**(888), 1128–1136 (2001).
11. Avilés Lucas, P., Dance, D. R., Castellano, I. A. and Vañó, E. *Monte Carlo simulations in CT for the study of the surface air kerma and energy imparted to phantoms of varying size and position.* Phys. Med. Biol. **49**(8), 1439–1454 (2004).
 12. Mukundan, S. Jr, Wang, P. I., Frush, D. P., Yoshizumi, T., Marcus, J., Kloeblen, E. and Moore, M. *MOSFET dosimetry for radiation dose assessment of bismuth shielding of the eye in children.* Am. J. Roentgenol. **188**, 1648–1650 (2007).
 13. Yoshizumi, T. T., Goodman, P. C., Frush, D. P., Nguyen, G., Toncheva, G., Sarder, M. and Barnes, L. *Validation of metal oxide semiconductor field effect transistor technology for organ dose assessment during CT: comparison with thermoluminescent dosimetry.* Am. J. Roentgenol. **188**, 1332–1336 (2007).
 14. Zhang, D. *et al.* *In vitro dose measurements in a human cadaver with abdomen/pelvis CT scans.* Med. Phys. **41**(9), 091911 (2014).
 15. Habibzadeh, M. A., Ay, M. R., Asl, A. R., Ghadiri, H. and Zaidi, H. *Impact of miscentering on patient dose and image noise in x-ray CT imaging: phantom and clinical studies.* Phys. Med. **28**(3), 191–199 (2012).
 16. Kaasalainen, T., Palmu, K., Reijonen, V. and Kortensniemi, M. *Effect of patient centering on patient dose and image noise in chest CT.* Am. J. Roentgenol. **203**(1), 123–130 (2014).
 17. Gudjonsdottir, J., Svensson, J. R., Campling, S., Brennan, P. C. and Jonsdottir, B. *Efficient use of automatic exposure control systems in computed tomography requires correct patient positioning.* Acta Radiol. **50**(9), 1035–1041 (2009).
 18. Kalra, M. K., Maher, M. M., Rizzo, S. and Saini, S. *Radiation exposure and projected risks with multidetector-row computed tomography scanning: clinical strategies and technologic developments for dose reduction.* J. Comput. Assist. Tomogr. **28**(Suppl. 1), S46–S49 (2004).
 19. Kaasalainen, T., Palmu, K., Lampinen, A. and Kortensniemi, M. *Effect of vertical positioning on organ dose, image noise and contrast in pediatric chest CT—phantom study.* Pediatr. Radiol. **43**(6), 673–684 (2013).
 20. Toth, T., Ge, Z. and Daly, M. P. *The influence of patient centering on CT dose and image noise.* Med. Phys. **34**(7), 3093–3101 (2007).