Precision of dosimetry-related measurements obtained on current multidetector computed tomography scanners

Kelsey B. Mathieu^{a)}

Department of Bioengineering, Rice University, Houston, Texas 77005

Michael F. McNitt-Gray and Di Zhang

Department of Biomedical Physics and Department of Radiology, David Geffen School of Medicine, University of California, Los Angeles, Los Angeles, California 90024

Hyun J. Kim

Department of Biostatistics and Department of Radiology, University of California, Los Angeles, Los Angeles, California 90024

Dianna D. Cody^{b)}

Department of Imaging Physics, University of Texas M. D. Anderson Cancer Center, Houston, Texas 77030

(Received 26 October 2009; revised 5 February 2010; accepted for publication 12 April 2010; published 14 July 2010)

Purpose: Computed tomography (CT) intrascanner and interscanner variability has not been well characterized. Thus, the purpose of this study was to examine the within-run, between-run, and between-scanner precision of physical dosimetry-related measurements collected over the course of 1 yr on three different makes and models of multidetector row CT (MDCT) scanners.

Methods: Physical measurements were collected using nine CT scanners (three scanners each of GE VCT, GE LightSpeed 16, and Siemens Sensation 64 CT). Measurements were made using various combinations of technical factors, including kVp, type of bowtie filter, and x-ray beam collimation, for several dosimetry-related quantities, including (a) free-in-air CT dose index ($\text{CTDI}_{100,\text{air}}$); (b) calculated half-value layers and quarter-value layers; and (c) weighted CT dose index (CTDI_w) calculated from exposure measurements collected in both a 16 and 32 cm diameter CTDI phantom. Data collection was repeated at several different time intervals, ranging from seconds (for $\text{CTDI}_{100,\text{air}}$ values) to weekly for 3 weeks and then quarterly or triannually for 1 yr. Precision of the data was quantified by the percent coefficient of variation (%CV).

Results: The maximum relative precision error (maximum %CV value) across all dosimetry metrics, time periods, and scanners included in this study was 4.33%. The median observed %CV values for $\text{CTDI}_{100,\text{air}}$ ranged from 0.05% to 0.19% over several seconds, 0.12%–0.52% over 1 week, and 0.58%–2.31% over 3–4 months. For CTDI_w for a 16 and 32 cm CTDI phantom, respectively, the range of median %CVs was 0.38%–1.14% and 0.62%–1.23% in data gathered weekly for 3 weeks and 1.32%–2.79% and 0.84%–2.47% in data gathered quarterly or triannually for 1 yr.

Conclusions: From a dosimetry perspective, the MDCT scanners tested in this study demonstrated a high degree of within-run, between-run, and between-scanner precision (with relative precision errors typically well under 5%). © 2010 American Association of Physicists in Medicine.

[DOI: [10.1118/1.3426000](https://doi.org/10.1118/1.3426000)]

Key words: CT, MDCT, radiation dosimetry, measurement precision, coefficient of variation

I. INTRODUCTION

Recent media attention regarding risk to patients receiving computed tomography (CT) scans has prompted the need for more accurate patient radiation dose estimates.¹ Monte Carlo (MC) computer modeling is making fast progress in the area of CT dose estimation and is moving closer toward clinical use. One such advancement was the recent development of an equivalent source model, which uses physical data, including half-value layer (HVL) and quarter-value layer (QVL), to construct virtual models of CT scanners.² Equivalent source models are constructed for every combination of scanner make and model, peak kilovoltage (kVp), and type of bowtie filter because a unique x-ray spectrum, which is energy-dependent and filtration-dependent, exists for each

scanner. Once an equivalent source model has been constructed, free-in-air CT dose index ($\text{CTDI}_{100,\text{air}}$) values are used in the calculation of normalization factors (described by DeMarco *et al.*³) which convert the output of the model to absolute dose (in mGy/mA s); a unique, scanner-specific normalization factor exists for every combination of technical factors, including kVp, bowtie filter, and x-ray beam collimation. This study sought to expand the number of available equivalent source MC models by supplying HVL, QVL, and $\text{CTDI}_{100,\text{air}}$ at multiple techniques for three scanner models produced by two manufacturers.

In order for MC models to be considered reliable or trustworthy, accuracy of the dose estimates obtained from the model must be verified by benchmarking the model. Bench-

TABLE I. Schedule of weekly and quarterly (on Siemens scanners at site B) or triannual (on GE scanners at site A) data collection on all nine CT scanner units. “✓” indicates that a measurement session was performed on that unit at that relative time period, while “-” indicates that no session was performed. Some cells are grouped to illustrate the data sampling used to calculate between-run (weekly) (cells grouped with dashed oval), between-run (triannual) (cells shaded gray), and between-scanner (cells grouped with solid oval) individual %CV values.

		Time of measurement session								
Scanner make and model	Unit ID	Week 1	Week 2	Week 3	3 months after week 1	4 months after week 1	6 months after week 1	8 months after week 1	9 months after week 1	12 months after week 1
GE VCT	A	✓	✓	✓	—	✓	—	✓	—	✓
	B	✓	✓	✓	—	—	—	—	—	—
	C	✓	✓	✓	—	—	—	—	—	—
GE LightSpeed 16	A	✓	✓	✓	—	✓	—	✓	—	✓
	B	✓	✓	✓	—	—	—	—	—	—
	C	✓	✓	✓	—	—	—	—	—	—
Siemens Sensation 64	A	✓	✓	✓	✓	—	✓	—	✓	✓
	B	✓	✓	✓	✓	—	✓	—	✓	✓
	C	✓	✓	✓	✓	—	✓	—	✓	✓

marking, or validating, a MC model entails comparing the output of the simulation with the same type of physical dose metric experimentally collected on the same type of CT scanner under the same conditions as simulated. Because HVL and QVL are used to construct equivalent source models and $\text{CTDI}_{100,\text{air}}$ values are used to convert MC output to dose, these quantities cannot be used for benchmarking purposes; instead, weighted CTDI (CTDI_w) values can be employed. Although most MC codes are validated with CTDI_w data for only one kVp, CTDI_w data were collected at several kVps in this study because validating a code at multiple energies demonstrates a more robust model and thus provides a stronger validation.⁴

Previous studies have shown that a MC model can yield dose estimates that agree within 3.5% to physical data collected in a 32 cm diameter CTDI phantom on a LightSpeed 16 CT scanner (General Electric Healthcare, Milwaukee, WI).³ Although 3.5% appears to indicate a high level of conformity, the data used to benchmark the model were obtained from a single scanner during a single measurement session; such measurements could potentially vary between scanners and over the lifetime of a scanner. Additionally, the level of agreement between MC dose estimates and physical dose measurements necessary for validation of the model has not yet been established. Therefore, in order to develop “pass-fail” benchmarking criteria, it is important to gauge measurement precision, or the closeness of repeated measurements obtained from a given scanner or “sibling” scanners of the same model. Measurement precision is most commonly quantified through the percent coefficient of variation (%CV), which is defined as the standard deviation divided by the mean multiplied by 100%.⁵ Quantifying the accuracy, or closeness of a measured value to the true value, of dosimetry data is difficult because there is often no gold standard.

According to the International Organization for Standardization (ISO), measurement precision encompasses measurement repeatability, intermediate precision, and reproducibility.⁶ Repeatability, or within-run precision, refers to precision estimates obtained when tests are performed over a very short time period by the same experimenter using the same equipment on the same subject at the same loca-

tion; in this study, within-run precision was characterized using $\text{CTDI}_{100,\text{air}}$ values calculated from repeated free-in-air exposure measurements. Intermediate precision, or within-laboratory reproducibility, refers to precision estimates obtained when measurements are made at one testing site on different days (between-run), by different experimenters (between-operator), or using different test equipment (between-scanner); between-run and between-scanner precision were evaluated in this study. Between-run precision was assessed for two different between-run time periods by conducting both weekly and quarterly (every 3 months) or triannual (every 4 months) measurement sessions. Between-scanner variability was determined by comparing dosimetry values collected on sibling scanners of the same model. Reproducibility, which ISO refers to as between-laboratory precision, could not be assessed in this study due to lack of feasibility. Therefore, short-term and long-term intrascanner [within-run, between-run (weekly), and between-run (quarterly or triannual)] and interscanner (between-scanner) precision were characterized in this study.

The purpose of this study was twofold: First, to collect a

FIG. 1. Setup for CTDI measurements as measured by a 10 cm pencil ionization chamber suspended free-in-air at isocenter from the central hole in a 16 cm CTDI phantom.

TABLE II. Techniques used on each make and model of scanner to obtain 20 repeated free-in-air CTDI measurements using a 10 cm pencil ionization chamber suspended at isocenter. All scans were performed in axial mode; nominal beam width can be calculated by multiplying the number of channels by the channel width.

Scanner make and model	kVp	mA	Exposure time (s)	No. of channels	Channel width (mm)	Bowtie
GE VCT	120	350	1	64	0.625	Large
GE LightSpeed 16	120	250	1	16	1.25	Large
Siemens Sensation 64	120	350	1	24	1.2	Large

series of dosimetry-related values ($\text{CTDI}_{100,\text{air}}$, HVL, QVL, and CTDI_w) on different makes and models of multidetector row CT (MDCT) scanners in order to develop and benchmark Monte Carlo equivalent source models; and second, to facilitate the eventual formation of pass-fail benchmarking criteria by characterizing the short-term and long-term intrascanner and interscanner precision of the data collected.

II. MATERIALS AND METHODS

II.A. Radiation dosimetry measurements

Exposure readings were measured using a 10 cm pencil ionization chamber and an electrometer (RadCal Corporation, Monrovia, CA) on three LightSpeed VCT and three LightSpeed 16 CT scanners (GE Healthcare, Milwaukee, WI) at site A and three Sensation 64 CT scanners (Siemens Medical Solutions, Forchheim, Germany) at site B. Readings were collected on all nine scanners at various time intervals over the course of 1 yr; the authors chose this time period because it was within the time frame of what is considered a long-term study (as specified by Bonnick and Lewis⁷) and because it roughly reflected the average lifespan of the CT x-ray tubes at both sites. At the beginning of each measurement session, within-run precision was gauged by collecting repeated free-in-air exposure measurements using a constant technique. Subsequently, the remaining data (free-in-air exposure measurements using varying techniques, HVL, QVL, and CTDI_w calculated values) were acquired on the scanner. To evaluate both between-run (weekly) and between-scanner variation, the entire set of measurements was repeated on each scanner at both 1 week and 2 week intervals after the original measurement session. Between-run (quarterly or triannual) variation was assessed by repeating the measurement sessions every 3–4 months after the original session for 1 yr; quarterly or triannual measurements were collected on five of the scanners (one GE VCT, one GE LightSpeed 16, and three Siemens Sensation 64 scanners). Table I summarizes the timing of all measurement sessions performed using each scanner.

II.A.1. Calculated $\text{CTDI}_{100,\text{air}}$ values

At the beginning of each measurement session, the active detection volume of the ionization chamber was suspended free-in-air at or above the geometrical center (isocenter) of the gantry bore as shown in Fig. 1; the central hole of a 16 cm CTDI phantom, which was placed in the patient head holder, was used to suspend the chamber. After aligning the

chamber, within-run precision was characterized by collecting 20 consecutive free-in-air exposure measurements over several minutes on each scanner using the techniques described in Table II in axial scan mode. The delay between repeated exposures was a few seconds (the time necessary to acquire and record an individual reading). The free-in-air setup was maintained and exposures were collected using various bowties, kVps, and collimations; collimation encompasses both the number of active channels and the channel width. Measurements were collected at a fixed collimation while varying the kVp and at various collimations at a fixed kVp of 120, as described in Table III. All exposure measurements were converted to $\text{CTDI}_{100,\text{air}}$ values using the equation specified in EUR 16262.⁸

II.A.2. Calculated HVL and QVL

HVL and QVL are the attenuator thicknesses required to reduce measured exposure to exactly one-half and one-quarter, respectively, of the unattenuated exposure.⁹ The free-in-air CTDI setup was maintained and this test was performed in service mode so that the x-ray tube could be held stationary (i.e., in a nonrotational mode with the x-ray tube positioned at a fixed angle) at 180°, which corresponds to the bottom of the gantry; this setup has been shown to be an

FIG. 2. To determine HVL and QVL, an ionization chamber (circle) was suspended free-in-air at isocenter and sheets of 1100 aluminum alloy (arrow) were placed at the bottom of the scanner gantry covering the x-ray beam, which was held stationary at 180°.

TABLE III. kVp, type of bowtie, and collimation variations used on each make and model of scanner to gather free-in-air CTDI measurements; axial scan mode and 1 s exposure times were used for all techniques. A total of 21, 12, and seven techniques were tested on each of the three GE VCT, GE LightSpeed 16, and Siemens Sensation 64 units, respectively.

Scanner make and model	kVp	mA s	No. of channels	Channel width (mm)	Bowtie
GE VCT	80, 100, 140	350	64	0.625	Small, medium, large
	120	350	8, 16, 32, 64	0.625	Small, medium, large
GE LightSpeed 16	80	350	16	1.25	Small, large
	100, 140	250	16	1.25	Small, large
	120	250	4, 8, 16	1.25	Small, large
Siemens Sensation 64	80, 100, 120, 140	350	24	1.2	Large
	120	350	32	0.6	Large
	120	350	1, 2	5	Large

appropriate method for determining HVL.¹⁰ Next, sheets of type 1100 aluminum alloy were placed at the bottom of the gantry so that they directly covered the x-ray tube output port assembly, as shown in Fig. 2. Finally, the measured-exposure versus aluminum-thickness data for each combination of technical factors described in Table IV were interpolated to calculate HVL and QVL.

II.A.3. Calculated CTDI_w

Exposure measurements were collected inside the two standard sizes (15 cm long with either a 16 or 32 cm diameter) of cylindrical polymethylmethacrylate (PMMA) CTDI phantoms; the 16 cm phantom was placed in the patient head holder, while the 32 cm phantom was placed directly on the patient table top. Both phantoms were positioned such that their central and 12:00 peripheral chamber locations were aligned with the scanner's sagittal and coronal laser lights. Following standard methods, exposure readings were recorded with the ionization chamber placed inside both the central and 12:00 peripheral chamber holes; PMMA filler rods were placed in the four empty chamber holes.^{11,12} All measurements were collected for a single axial rotation using the techniques described in Table V. An average, or weighted, CTDI (CTDI_w) was calculated from the peripheral and central exposure measurements using the equation described in EUR 16262 for both CTDI phantoms.⁸

II.B. Statistical analysis

Precision of the dosimetry data was characterized by %CV values, which were calculated in a two-tier process. In the lower tier, data were grouped according to the type of precision being characterized [i.e., between-run (weekly) precision] and individual %CV values were calculated from this data. Table I shows the data grouping used to calculate individual %CV values for each type of precision; within-run precision is not shown in the table because individual %CV values were calculated from 20 repeated CTDI_{100,air} values, which were collected on a single scanner during a single session. Because scanner model and technical factors have a known effect on absolute exposure, individual %CV values were always calculated from measurements collected at the same technical factors (bowtie filter, kVp, and collimation) on the same make and model of scanner.^{13,14} In the upper tier, individual %CVs were pooled within each precision type [i.e., between-run (weekly) precision], scanner model, and dosimetry metric (i.e., CTDI_{100,air}) to calculate the median and range. The median and range of %CV values were reported rather than an average and confidence interval because the presence of potential outliers was detected within the pooled data sets.^{15,16}

The following example illustrates the process that was employed to calculate the %CV values reported in this study. Between-run (weekly) precision of CTDI_{100,air} values calcu-

TABLE IV. HVLs and QVLs were found for various kVps and types of bowties on each make and model of scanner; axial scan mode and 1 s exposure times were used for all techniques. Six, five, and four techniques were tested on each of the three GE VCT, GE LightSpeed 16, and Siemens Sensation 64 units, respectively.

Scanner make and model	kVp	mA s	No. of channels	Channel width (mm)	Bowtie
GE VCT	80, 100, 140	350	64	0.625	Large
	120	350	64	0.625	Small, medium, large
GE LightSpeed 16	80	350	16	1.25	Large
	100, 140	250	16	1.25	Large
	120	250	16	1.25	Small, large
Siemens Sensation 64	80, 100, 120, 140	350	24	1.2	Large

TABLE V. Techniques employed by each make and model of scanner for CTDI phantom measurements; axial scan mode and 1 s exposure times were used for all techniques. All technical factors, except for the bowtie filter used by the GE scanners, were consistent between the 16 and 32 cm phantoms. Four techniques were tested per CTDI phantom using each scanner make and model, with the exception of the GE VCT, where two bowties, and thus a total of eight techniques, were tested for the 16 cm CTDI phantom.

Scanner make and model	kVp	mA s	No. of channels	Channel width (mm)	Bowtie (16 cm CTDI phantom)	Bowtie (32 cm CTDI phantom)
GE VCT	80, 100, 120, 140	350	64	0.625	Small, medium	Large
GE LightSpeed 16	80	350	16	1.25	Small	Large
	100, 120, 140	250	16	1.25	Small	Large
Siemens Sensation 64	80, 100, 120, 140	350	24	1.2	Large	Large

lated from exposure measurements made on the GE LightSpeed 16 scanners was determined by computing individual %CV values from three CTDI_{100,air} data points collected at a given technique and each gathered 1 week apart on a given scanner unit. Because data were collected for 12 techniques per scanner on three scanners, a total of 36 individual between-run (weekly) %CV values were calculated. These 36 %CV values were then pooled to determine the median and range of between-run (weekly) precision of free-in-air CTDI values collected on GE LightSpeed 16 scanners. Similarly, between-run (quarterly and triannual) individual %CVs were calculated using five quarterly or four triannual dosimetry values and between-scanner individual %CVs were cal-

culated from dosimetry values collected on three sibling scanners of the same model; individual %CVs were then pooled across technique and sibling scanners (for between-run precision) or measurement sessions (for between-scanner precision).

Pooling data across techniques and either sibling scanners or measurement sessions better represents overall scanner performance than assessing the precision of data collected at one technique on one scanner during one session, which could overestimate or underestimate true performance.⁷ Additionally, pooling across these factors increases the degrees of freedom and thus the statistical validity of the results. Although precision error could potentially vary from

TABLE VI. Mean and standard deviation, in parentheses, of CTDI_{100,air} calculated values; “-” indicates the scanner either does not offer that bowtie option or that beam width. CTDI_{100,air} values were normalized to 100 mA s to account for differences in scanning protocols used on the different scanner makes and models.

kVp	Beam width (mm) ^a	Bowtie	CTDI _{100,air} (mGy/100 mA s)		
			GE VCT	GE LightSpeed 16	Siemens Sensation 64
80	20, 40	Small	12.4 (0.3)	11.4 (0.1)	-
80	40	Medium	12.4 (0.3)	-	-
80	20, 28.8, 40	Large	8.9 (0.2)	8.4 (0.1)	5.8 (0.1)
100	20, 40	Small	20.4 (0.4)	19.1 (0.2)	-
100	40	Medium	20.3 (0.4)	-	-
100	20, 28.8, 40	Large	15.6 (0.2)	15.0 (0.2)	11.1 (0.3)
120	5	Small	46.7 (1.4)	43.5 (0.9)	-
120	10	Small	37.3 (0.7)	35.0 (0.5)	-
120	20	Small	31.4 (0.4)	28.0 (0.4)	-
120	40	Small	29.5 (0.5)	-	-
120	5	Medium	46.7 (1.5)	-	-
120	10	Medium	37.3 (0.8)	-	-
120	20	Medium	31.4 (0.5)	-	-
120	40	Medium	29.4 (0.5)	-	-
120	5	Large	37.7 (1.2)	35.9 (0.7)	16.2 (0.3)
120	10	Large	30.1 (0.5)	28.8 (0.4)	16.3 (0.3)
120	19.2	Large	-	-	19.6 (0.3)
120	20	Large	25.3 (0.3)	23.1 (0.3)	-
120	28.8	Large	-	-	18.1 (0.3)
120	40	Large	23.8 (0.3)	-	-
140	20, 40	Small	39.7 (0.6)	38.1 (0.5)	-
140	40	Medium	39.6 (0.6)	-	-
140	20, 28.8, 40	Large	33.1 (0.4)	32.4 (0.5)	27.2 (0.5)

^aAt 80, 100, and 140 kVp, nominal beam widths of 20, 28.8, and 40 mm were tested exclusively on the GE LightSpeed 16, Siemens Sensation 64, and GE VCT scanners, respectively.

TABLE VII. Median and range, in parentheses, of measurement precision of $\text{CTDI}_{100,\text{air}}$, HVL, QVL, and CTDI_w (for a 16 and 32 cm CTDI phantom) calculated values. Within-run precision was only evaluated for $\text{CTDI}_{100,\text{air}}$ data (collected using the techniques that appear in Table II), thus “-” is shown for all other dosimetry metrics. Between-run and between-scanner individual %CVs were calculated from data collected at a given technique (shown in Tables III, IV and V for $\text{CTDI}_{100,\text{air}}$, HVL and QVL, and CTDI_w , respectively) on the same make and model of scanner.

Dosimetry metric	Scanner make and model	Intrascanner precision, CV (%)			Interscanner (between-scanner) precision, CV (%)
		Within-run	Between-run (weekly)	Between-run (quarterly/triannual) ^a	
$\text{CTDI}_{100,\text{air}}$	GE VCT	0.05 (0.04–0.11)	0.52 (0.10–0.76)	0.58 (0.47–1.04)	1.83 (0.92–4.33)
	GE LightSpeed 16	0.08 (0.06–0.10)	0.12 (0.01–1.13)	2.31 (2.12–3.13)	0.79 (0.50–1.95)
	Siemens Sensation 64	0.19 (0.00–0.86)	0.47 (0.25–0.63)	1.76 (1.26–2.39)	1.46 (0.31–3.06)
	GE VCT	-	0.19 (0.02–1.86)	0.42 (0.20–2.19)	0.73 (0.13–2.74)
	GE LightSpeed 16	-	0.22 (0.08–1.46)	0.77 (0.36–1.04)	0.83 (0.51–2.03)
	Siemens Sensation 64	-	0.24 (0.06–0.75)	0.92 (0.67–1.17)	1.04 (0.30–1.71)
HVL	GE VCT	-	0.37 (0.05–0.76)	0.43 (0.11–0.50)	0.66 (0.25–1.41)
	GE LightSpeed 16	-	0.30 (0.08–0.72)	0.47 (0.29–1.08)	0.59 (0.35–0.94)
	Siemens Sensation 64	-	0.19 (0.02–0.83)	0.54 (0.31–0.67)	0.79 (0.28–1.14)
	GE VCT	-	0.70 (0.11–1.70)	1.32 (0.83–1.45)	1.71 (0.65–3.01)
	GE LightSpeed 16	-	0.38 (0.08–1.06)	2.79 (2.44–2.88)	0.94 (0.35–1.52)
	Siemens Sensation 64	-	1.14 (0.88–3.77)	2.54 (1.92–3.64)	1.49 (0.29–3.41)
QVL	GE VCT	-	1.19 (0.39–2.53)	0.84 (0.61–1.84)	1.73 (0.51–3.44)
	GE LightSpeed 16	-	1.23 (0.34–2.29)	2.47 (1.25–2.79)	1.09 (0.62–2.22)
	Siemens Sensation 64	-	0.62 (0.24–1.43)	2.08 (1.30–3.07)	1.95 (0.59–4.11)
	GE VCT	-	0.70 (0.11–1.70)	1.32 (0.83–1.45)	1.71 (0.65–3.01)
	GE LightSpeed 16	-	0.38 (0.08–1.06)	2.79 (2.44–2.88)	0.94 (0.35–1.52)
	Siemens Sensation 64	-	1.14 (0.88–3.77)	2.54 (1.92–3.64)	1.49 (0.29–3.41)
CTDI_w (16 cm CTDI phantom)	GE VCT	-	1.19 (0.39–2.53)	0.84 (0.61–1.84)	1.73 (0.51–3.44)
	GE LightSpeed 16	-	1.23 (0.34–2.29)	2.47 (1.25–2.79)	1.09 (0.62–2.22)
	Siemens Sensation 64	-	0.62 (0.24–1.43)	2.08 (1.30–3.07)	1.95 (0.59–4.11)
	GE VCT	-	1.19 (0.39–2.53)	0.84 (0.61–1.84)	1.73 (0.51–3.44)
	GE LightSpeed 16	-	1.23 (0.34–2.29)	2.47 (1.25–2.79)	1.09 (0.62–2.22)
	Siemens Sensation 64	-	0.62 (0.24–1.43)	2.08 (1.30–3.07)	1.95 (0.59–4.11)
CTDI_w (32 cm CTDI phantom)	GE VCT	-	1.19 (0.39–2.53)	0.84 (0.61–1.84)	1.73 (0.51–3.44)
	GE LightSpeed 16	-	1.23 (0.34–2.29)	2.47 (1.25–2.79)	1.09 (0.62–2.22)
	Siemens Sensation 64	-	0.62 (0.24–1.43)	2.08 (1.30–3.07)	1.95 (0.59–4.11)
	GE VCT	-	1.19 (0.39–2.53)	0.84 (0.61–1.84)	1.73 (0.51–3.44)
	GE LightSpeed 16	-	1.23 (0.34–2.29)	2.47 (1.25–2.79)	1.09 (0.62–2.22)
	Siemens Sensation 64	-	0.62 (0.24–1.43)	2.08 (1.30–3.07)	1.95 (0.59–4.11)

^aBetween-run (quarterly) precision was assessed for the Siemens scanners, which were tested at site B; between-run (triannual) precision was assessed for both models of GE scanners tested at site A.

technique-to-technique, scanner-to-scanner, and session-to-session, the purpose of this study was to characterize the general performance of the scanners over a broad range of conditions rather than to develop a precision profile.

III. RESULTS

Over 850 individual %CV values were calculated, which ranged from 0.00% to 4.33% across all dosimetry metrics, precision types, and scanners included in this study; over 95% of the calculated %CVs were less than 2.75%.

Free-in-air CTDI calculated values and the corresponding precision results, respectively, appear in Tables VI and VII for each scanner make and model; because different current-exposure time products were used across scanner types, all $\text{CTDI}_{100,\text{air}}$ values were normalized to 100 mA s. Table VI shows a large spread of $\text{CTDI}_{100,\text{air}}$ values (5.8–46.7 mGy/100 mA s), which were influenced by the scanner model and

technical parameters selected. Table VII shows intrascanner and interscanner variation in $\text{CTDI}_{100,\text{air}}$ values to be extremely low, with all %CVs less than 5%. One subtle trend emerged from these results, which was that in most cases, the scanners displayed progressively worse intrascanner precision as the between-run time increased from a few seconds to a week to several months.

Calculated HVLs and QVLs and their precisions appear in Tables VIII and VII, respectively. As shown in Table VIII, the mean HVLs ranged from 5.4 to 9.7 mm of aluminum and the mean QVLs ranged from 12.0 to 21.1 mm of aluminum, depending on the scanner model and technical factors tested. Table VII shows extremely low short-term and long-term intrascanner and interscanner variability in the HVLs and QVLs, with all median and individual %CVs less than or equal to 1.04% and 2.74%, respectively.

The calculated CTDI_w values (normalized to 100 mA s)

TABLE VIII. Mean and standard deviation, in parentheses, of calculated HVLs and QVLs (in mm of aluminum); “-” indicates that the scanner does not offer that bowtie option.

kVp	Bowtie	HVL (mm Al)		
		GE VCT	GE LightSpeed 16	Siemens Sensation 64
80	Large	5.4 (0.09)	5.9 (0.07)	6.2 (0.08)
100	Large	6.6 (0.05)	7.2 (0.05)	7.6 (0.08)
120	Small	6.6 (0.03)	7.2 (0.06)	-
120	Medium	6.6 (0.01)	-	-
120	Large	7.7 (0.05)	8.3 (0.09)	8.7 (0.09)
140	Large	8.6 (0.14)	9.2 (0.04)	9.7 (0.10)
kVp	Bowtie	QVL (mm Al)		
		GE VCT	GE LightSpeed 16	Siemens Sensation 64
80	Large	12.0 (0.10)	13.0 (0.10)	13.6 (0.11)
100	Large	15.0 (0.11)	16.0 (0.11)	16.5 (0.13)
120	Small	15.4 (0.11)	16.6 (0.09)	-
120	Medium	15.5 (0.08)	-	-
120	Large	17.5 (0.10)	18.5 (0.10)	18.9 (0.14)
140	Large	19.8 (0.13)	20.7 (0.08)	21.1 (0.15)

for the 16 and 32 cm CTDI phantoms and their relative precision errors appear in Tables IX and VII, respectively. Table IX shows the range of CTDI_w values obtained from both the 16 cm (3.9–28.2 mGy/100 mA s) and 32 cm (1.7–12.7 mGy/100 mA s) CTDI phantoms. Table VII shows that with a few

TABLE IX. Mean and standard deviation, in parentheses, of calculated CTDI_w values for a 16 and 32 cm CTDI phantom; “-” indicates that the scanner does not offer that bowtie option. CTDI_w values were normalized to 100 mA s to account for differences in scanning protocols used on the different scanner models.

kVp	Bowtie	CTDI _w for a 16 cm phantom (mGy/100 mA s)		
		GE VCT	GE LightSpeed 16	Siemens Sensation 64
80	Small	6.6 (0.1)	6.4 (0.1)	-
80	Medium	7.6 (0.2)	-	-
80	Large	-	-	3.9 (0.1)
100	Small	11.9 (0.2)	11.6 (0.2)	-
100	Medium	13.5 (0.3)	-	-
100	Large	-	-	8.0 (0.2)
120	Small	18.1 (0.3)	17.7 (0.3)	-
120	Medium	20.4 (0.4)	-	-
120	Large	-	-	13.4 (0.3)
140	Small	25.1 (0.3)	24.7 (0.4)	-
140	Medium	28.2 (0.4)	-	-
140	Large	-	-	20.3 (0.5)
kVp	Bowtie	CTDI _w for a 32 cm CTDI phantom (mGy/100 mA s)		
		GE VCT	GE LightSpeed 16	Siemens Sensation 64
80	Large	2.9 (0.1)	2.8 (0.0)	1.7 (0.0)
100	Large	5.6 (0.1)	5.5 (0.1)	3.7 (0.1)
120	Large	8.9 (0.1)	8.7 (0.2)	6.5 (0.1)
140	Large	12.7 (0.2)	12.6 (0.2)	10.1 (0.2)

exceptions, the median %CV values (0.38%–2.79%) were slightly higher compared to the other dosimetry metrics (CTDI_{100,air}, HVL, and QVL). Despite the slightly higher (in general) relative precision errors observed in this portion of the study, the results still demonstrated extremely low variability, with all %CV values below 5%.

IV. DISCUSSION

The dosimetry data collected in this study yielded very high measurement precision across all conditions, time intervals, and scanners. The vast majority (over 95%) of the large amount of %CV values analyzed and reported in this study were below 2.75%, with only a few reaching 4%. Though not all existing MDCT scanners were tested, three different scanner models, which consisted of scanners from two manufacturers and two models from the same manufacturer, were evaluated. To further generalize the results of this study, two testing locations were included. In all scenarios, both intrascanner and interscanner relative precision errors were extremely low.

This study’s results indicate that dose estimates obtained from MC model simulations can be validated if they agree with physical data at a level of 5% or less; however, the level of acceptable mismatch is probably greater than 5% because measurement precision error is presumably not the only source of disagreement between the model and physical data. In order to develop more accurate validation criteria, several factors not addressed in this study should be considered. For example, inherent precision of the MC model, which can be affected by the number of photons simulated, should be taken into account during benchmarking experiments. Additionally, the dosimetry-related quantities considered in this study have different roles in MC equivalent source models which may influence error estimates. Specifically, HVL and QVL are parameters input into MC equivalent source models and therefore precision error in these values propagates through the model. Precision error associated with the CTDI_{100,air} values, which convert MC output to dose, does not propagate through the model itself but does lead to variability in the absolute dose estimates obtained and thus error or uncertainty bars should be included with reported dose estimates.

Dosimetry measurements are collected on CT scanners for various reasons other than for benchmarking MC dose estimates. For example, such results serve as a reference for CT facility management to show that in light of the exceptional stability of modern CT scanners, frequent dosimetry testing is unnecessary for avoiding overexposure incidents.¹⁷ Therefore, the results of this study also have implications for scanner compliance testing, as well as any other applications that utilize scanner output (dosimetry) values.

To the best of the authors’ knowledge, no prior study has addressed the precision of measuring dose output from state-of-the-art MDCT scanners. Despite the strength of this study, sources of variation or error were present, including variation in scanner output, ionization chamber and electrometer imprecision, and setup variability between sessions and scan-

ners. Scanner workloads varied from 160 to 164, 126 to 156, and 119 to 204 patients per week (on average over the time of the study) on the GE VCT, GE LightSpeed 16, and Siemens Sensation 64 scanners, respectively. Furthermore, at site B, one scanner had an x-ray tube change during the course of the study. At site A, a different ionization chamber and electrometer were used during the third triannual measurement session on the GE VCT scanner. Additionally, at both sites, the ionization chambers and electrometers were calibrated prior to the study and were not recalibrated during the study and so drift was possible. Although the same experimenters were maintained at sites A and B throughout the course of the study, setup variability was unavoidable. To minimize setup variability at site A, centering of the ionization chamber and CTDI phantoms was verified by generating 1.25 mm thick images and then using a caliper tool to check the images for centering within at least 3 mm along both the x and y directions in the transverse plane (in the majority of cases, centering was within 1 mm). The scanners at site B were unable to identify gantry isocenter on acquired CT images; therefore, only the scanners' built-in positioning laser lights were utilized to center the chamber and phantoms.

Care should be taken when directly comparing the results reported in this study across scanner makes and models. When considering comparison of the %CV values, it is important to keep in mind the differences in testing locations and experimenters between sites A and B. Similarly, direct comparisons of system output ($\text{CTDI}_{100,\text{air}}$, HVL, QVL, and CTDI_w values) across scanner models may be inappropriate. Although the same combination of technical factors resulted in measurable dose differences between scanner models, image quality was not assessed in this study and instead emphasis was placed on assessing precision. In order to properly characterize differences in dose performance between scanners, dose should be quantified while maintaining the same level of image quality across scanner models.

Despite the limitations of this study, the results revealed extremely low levels of variation in scanner output and dosimetry-related quantities across time and across sibling scanners of the same make and model. These results point to the exceptional similarity in sibling scanners and stability of the x-ray source output in the state-of-the-art MDCT scanners tested in this study over both very short periods of time and in time periods tested up to 1 yr.

V. CONCLUSION

This study investigated the variability of CT scanner output across a range of time periods (from as short as a few seconds to as long as several months), technical parameters (kVp, bowtie filter, and x-ray beam collimation), and sibling scanners of three different makes and models. The results of this study demonstrated that across all conditions, the MDCT scanners tested produced dosimetry-related data that were

precise (well within 5%) for all time periods tested over the course of 1 yr. These results can be applied in Monte Carlo modeling to improve upon and verify current MC models, thus improving the accuracy of patient dose estimates.

ACKNOWLEDGMENTS

This research was supported by NIH Grant No. R01-EB0048989. Additionally, the authors would like to thank Dr. Philip Tchou for his assistance during one of the measurement sessions.

^aElectronic mail: knb2@rice.edu

^bElectronic mail: dcody@mdanderson.org

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