Normalized CT Dose Index of the CT Scanners Used in the National Lung Screening Trial

Dianna D. Cody[1]
Hyun-Jung Kim[2]
Christopher H. Cagnon[3]
Frederick J. Larke[4]
Michael M. McNitt-Gray[2]
Randell L. Kruger[5]
Michael J. Flynn[6]
J. Anthony Seibert[7]
Philip F. Judy[8]
Xizeng Wu[9]

Keywords: CT dose measurements, CT radiation dose, lung cancer screening, MDCT dose

DOI:10.2214/AJR.09.3268

Received June 30, 2009; accepted after revision November 25, 2009.

This work and the National Lung Screening Trial were funded by the National Institutes of Health and the National Cancer Institute (grant CA80098 and contracts with the Division of Cancer Prevention).

[1]Department of Imaging Physics, University of Texas M. D. Anderson Cancer Center, 1515 Holcombe Blvd., Unit 56, Houston, TX 77030. Address correspondence to D. D. Cody (dcody@mdanderson.org).

[2]Thoracic Imaging Research Group, David Geffen School of Medicine at UCLA, Los Angeles, CA.

[3]Radiological Sciences, UCLA Medical Center, Los Angeles, CA.

[4]Radiology Department, University of Colorado Health Sciences Center, Anschutz Medical Campus, Aurora, CO.

[5]Department of Radiology, Marshfield Clinic, Marshfield, WI.

[6]Department of Radiology, Henry Ford Health System, Detroit, MI.

[7]Department of Radiology, UC Davis Medical Center, Sacramento, CA.

[8]Department of Radiology, Brigham & Women's Hospital, Boston, MA.

[9]Radiology Department, University of Alabama at Birmingham, Birmingham, AL.

AJR 2010; 194:1539–1546

0361–803X/10/1946–1539

OBJECTIVE. The National Lung Screening Trial includes 33 participating institutions that performed 75,133 lung cancer screening CT examinations for 26,724 subjects during 2002–2007. For trial quality assurance reasons, CT radiation dose measurement data were collected from all MDCT scanners used in the trial.

MATERIALS AND METHODS. A total of 247 measurements on 96 MDCT scanners were collected using a standard CT dose index (CTDI) measurement protocol. The scan parameters used in the measurements (tube voltage, milliampere-seconds [mAs], and detector–channel configuration) were set according to trial protocol for average size subjects. The normalized weighted CT dose index ($CTDI_w$) (computed as $CTDI_w$/mAs) obtained from each trial-participating scanner was tabulated.

RESULTS. We found a statistically significant difference in normalized CT dose index among CT scanner manufacturers, likely as a result of design differences, such as filtration, bow-tie design, and geometry. Our findings also indicated a statistically significant difference in normalized CT dose index among CT scanner models from the same manufacturer (e.g., GE Healthcare, Siemens Healthcare, and Philips Healthcare). We also found a statistically significant difference in normalized CT dose index among all models and all manufacturers; furthermore, we found a statistically significant difference in normalized CT dose index among CT scanners from all manufacturers when we compared scanners with four or eight data channels to those with 16, 32, or 64 channels, suggesting that more complex scanners have improved dose efficiency.

CONCLUSION. Average normalized CT dose index values varied by a factor of almost two for all scanners from all manufacturers. This study was focused on machine-specific normalized CT dose index; patient dose and image quality were not addressed.

CT is currently experiencing a dramatic increase in popularity and utilization [1], including the use of CT to screen for early stages of disease, such as lung cancer, heart disease, and colon cancer. Several studies have been initiated to investigate the efficacy of CT in the early detection of lung cancer. One such large study is the National Lung Screening Trial, which is sponsored by the National Cancer Institute. The National Lung Screening Trial is a randomized controlled study comparing two ways of detecting asymptomatic lung cancer (projection chest radiography and MDCT scanning) conducted by two organizations—the American College of Radiology Imaging Network and the Lung Screening Study.

The main objective of the National Lung Screening Trial is to determine whether lung cancer screening using low-dose helical MDCT reduces lung cancer–specific mortality relative to screening with chest radiographs in a high-risk cohort [7]. A total of 53,457 volunteer subjects were enrolled in the National Lung Screening Trial; entrance criteria included 30 or more pack-years of cigarette smoking (packs per day multiplied by the number of years smoked) and being between 55 and 74 years old at the date of entry to the study. (Former smokers must have quit within the previous 15 years.) Each participant was randomly assigned to either the CT or chest radiograph arm of the study and agreed to have a baseline imaging examination and two more annual follow-up examinations. Thus, about 26,000 subjects underwent as many as three lung cancer screening CT examinations as part of this study (total of about 75,000 CT examinations).

The lung cancer screening CT examinations were offered nationwide at 33 separate institutions (Fig. 1 and Table 1). Because of the large number of subjects enrolled in this trial, increased surveillance of the equipment was desired. Therefore, as part of the trial quality assurance procedures, CT dose index measurements were performed on the MDCT scanners used for this imaging trial on a routine basis throughout the trial.

The National Lung Screening Trial was designed so that all resulting data obtained by the two collaborative groups could be combined for analysis. Although there are some sources of CT dose index data for CT scanners available (both online and in scanner technical manuals), these reports tend to be widely scattered and often are difficult to obtain. In addition, the reports either are specific to one scanner (such as the manufacturer's specifications or dosimetry report) or contain general data about several scanners. What these reports do not easily provide are all of the expected values for all of the scanners used in this trial and under the specific scanning conditions (specifically peak kilovoltage, x-ray beam width, and bow-tie filter) used in the National Lung Screening Trial. Therefore, the trial quality assurance activities provided an opportunity to record and compare CT dose index performance for a relatively large sample of scanners (over 100 distinct units) representing a range of manufacturers and models, where all measurements were made using specific parameter settings. In addition, collection of these data provided an opportunity to address in a statistical manner some questions about scanner CT dose index variability by manufacturer, by CT scanner model, and by CT scanner complexity (number of data channels). Therefore, the purpose of this report is two-fold—first, to provide the normalized MDCT dose index measurement results to the medical technical field, and second, to provide MDCT dose index measurement data required for calculations of participant radiation dose that will be used later to estimate risk of participants for this and perhaps future CT-based screening trials.

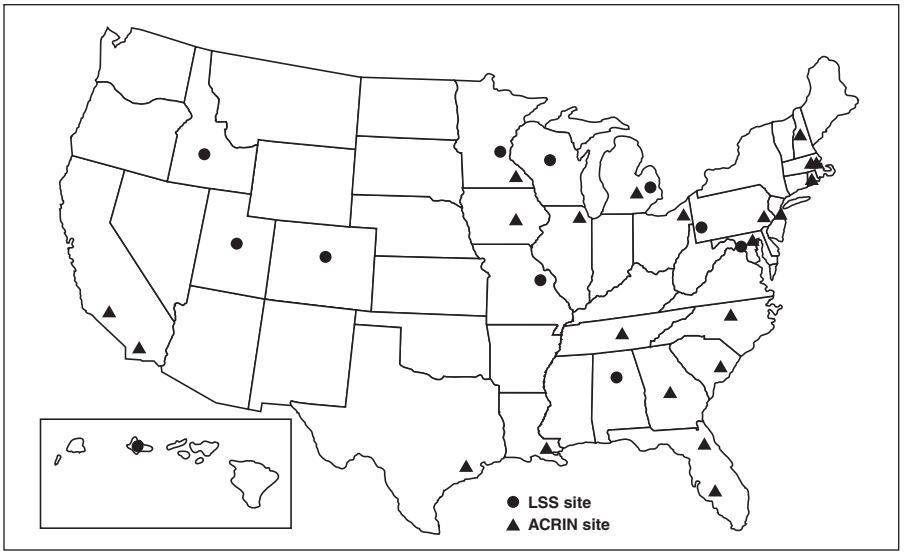

Fig. 1—Geographic distribution of 33 sites of National Lung Screening Trial. ACRIN = American College of Radiology Imaging Network, LSS = Lung Screening Study.

Materials and Methods

Image quality assurance programs were implemented over time across the National Lung Screening Trial sites and were very similar between American College of Radiology Imaging Network and Lung Screening Study sites. For American College of Radiology Imaging Network sites, initial CT scanner certification that included a CT dose index measurement for tomographic image acquisition was required for all scanners that would be used to acquire images for National Lung Screening Trial participants. This CT scanner certification process was repeated for each active scanner used in the trial on an annual basis thereafter until participant screening examinations were completed. A similar certification process was implemented at Lung Screening Study sites. Compliance with the annual certification process was variable across sites, but was reinforced with a reminder notification process sent under cover of the National Lung Screening Trial Physics Working Group. Ultimately, dose measurements were available for at least one time point on all National Lung Screening Trial scanners trialwide.

Exposure measurements and dose calculations were conducted at each trial site by a diagnostic medical physicist. This effort required the cooperation of a large number of medical physicists and adherence to the instructions provided by the administrating organization (American College of Radiology Imaging Network or Lung Screening Study). This collection of dose data is the result of the cooperation of many professional medical physicists from across the nation (Fig. 1 and Table 1).

Radiation exposure measurements and dose calculations for CT followed the standard CT dose index process [3, 4]. Instructions were provided to each site to facilitate the measurement procedure. Briefly, the 32-cm-diameter polymethyl methacrylate CT dose index phantom was placed on the CT scanner patient table top and centered in the gantry. A 100-mm-long CT pencil ionization chamber was placed in the central hole, and a single transverse (axial) exposure was performed at the center of that phantom using the National Lung Screening Trial protocol parameter settings (for an average size patient). The measurement was performed three times, and each resulting exposure value was recorded on a specific form. The ion chamber was then repositioned in the top (12-o'clock position) chamber position, and the exposure and recording procedure was repeated three times. Using the average exposure values ($CTDI_{100c}$ = CT dose index obtained using a 100-mm-long pencil ion chamber positioned at the center of a CTDI phantom), $CTDI_{100p}$ = (CT dose index obtained using a 100-mm-long pencil ion chamber positioned at the peripheral location of a CTDI phantom), $CTDI_w$, and volume CTDI ($CTDI_{vol}$) values were calculated [3]. In addition to the exposure measurements, the physicist at each site collected specific information regarding the MDCT scanner (e.g., scanner manufacturer, scanner model, test date, and the actual technique factors used for the dose measurement).

Sites were instructed to perform the dose measurement using the same technique that would be used for an average size National Lung Screening Trial participant. The techniques for the American College of Radiology Imaging Network sites were developed for each scanner model and can be found elsewhere [2]. The technique parameters used for the Lung Screening Study sites were based on a range of values agreed on by both groups (National Lung Screening Trial Medical Physics Working Group Meeting, June 2003). For example, the peak kilovoltage could range from 120 to 140 kVp, but 120 kVp was preferred; the tube current and rotation time product (mAs) should be in the range of 40 to 80; pitch (table

TABLE 1: CT Lung Screening Sites and Locations

Site No.	Site Name	Site Location
1	Beth Israel Deaconess Medical Center	Boston, MA
2	Brigham and Women's Hospital	Boston, MA
3	Brown University	Providence, RI
4	Cancer Institute of New Jersey	New Brunswick, NJ
5	Dartmouth-Hitchcock Medical Center	Lebanon, NH
6	The Emory Clinic	Atlanta, GA
7	Georgetown University Medical Center, Lombardi Cancer Research Center	Washington, DC
8	Henry Ford Health System	Detroit, MI
9	Jewish Heart and Lung Institute	Louisville, KY
10	Johns Hopkins University	Baltimore, MD
11	Marshfield Clinic Research Foundation	Marshfield, WI
12	Mayo Clinic Jacksonville	Jacksonville, FL
13	Mayo Clinic Rochester	Rochester, MN
14	Moffitt Cancer Center at the University of South Florida	Tampa, FL
15	Medical University of South Carolina	Charleston, SC
16	Northwestern University Medical Center	Chicago, IL
17	Ochsner Clinic Foundation	New Orleans, LA
18	St. Elizabeth's Health Center	Youngstown,OH
19	Pacific Health Research Institute	Honolulu, HI
20	University of Alabama at Birmingham	Birmingham, AL
21	University of California Los Angeles	Los Angeles, CA
22	University of California San Diego	San Diego, CA
23	University of Colorado Denver	Aurora, CO
24	University of Iowa	Iowa City, IA
25	University of Minnesota School of Public Health/Virginia Piper Cancer Institute	Minneapolis, MN
26	University of Pennsylvania	Philadelphia, PA
27	University of Pittsburgh Medical Center	Pittsburgh, PA
28	University of Michigan Medical Center	Ann Arbor, MI
29	University of Texas M. D. Anderson Cancer Center	Houston, TX
30	University of Utah Health Science Center	Salt Lake City, UT
31	Vanderbilt University	Nashville, TN
32	Wake Forest University School of Medicine	Winston-Salem, NC
33	Washington University School of Medicine	St. Louis, MO

travel perrotation as measured by beam width) should be in the range of 1.25 to 2.0; and the effective mAs (mAs divided by pitch) should be between 20 and 60. The end result was that all National Lung Screening Trial sites used technique parameters within these specifications. It should be noted that only a small number of scanners used in the trial were operated at a peak kilovoltage other than 120 kVp (n = 10). Some were operated at 140 kVp, as already mentioned, two were operated at 135 kVp, and one was operated at 110 kVp. Because of these small numbers, these scanners were excluded from this analysis.

If the milliampere-second (mAs) used for the dose measurement was outside the acceptable range established for the subjects scanned during the trial, the dose results provided were scaled linearly until they reflected the average-patient-size dose using an acceptable mAs value. (If repeat dose measurements were required, CT physics reviewers contacted the National Lung Screening Trial site physicist directly to discuss the relevant issues.)

Before data analysis, all individual dose measurements and calculations were reviewed by the entire National Lung Screening Trial Medical Physics Working Group to identify spurious data points. Outlier data points were excluded from further analysis on a case-by-case basis, according to consensus of the entire group. Exclusions were limited to unreasonable results or acquisition parameter combinations that were impossible for the scanner platform and typically involved the reporting of detector configuration. In total, 16 of 237 individual dose measurements were excluded from analysis, such that 93% of collected data were statistically analyzed. All dose values for an individual scanner, which ranged from one to five individual values depending on submitted reports, were averaged before analysis of the data. The primary end point of

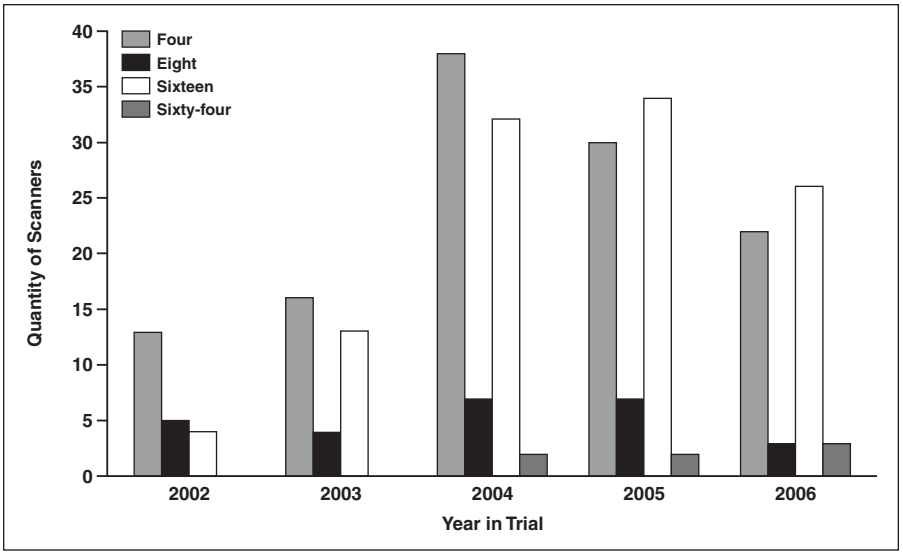

Fig. 2—Bar graph showing number of scanners in trial by number of data channels during course of National Lung Screening Trial. Note that 32-channel Siemens Healthcare Sensation 64 scanners were included in 64-channel scanner group for simplicity.

TABLE 2: Fleet of CT Scanners Initially Certified for National Lung Screening Trial, as of December 31, 2002

Manufacturer, Model	Maximum No. of Images per Rotation	Beam Width (mm)	Table Speed Used for Trial (mm/rotation)	No. of Scanners
GE Healthcare				
QX/i	4	10	15	6
LightSpeed Plus	4	10	15	3
LightSpeed Ultra	8	10	13.5	5
LightSpeed 16	16	20	27.5	1
Philips Healthcare				
MX8000	4	4 or 10	8 or 15	2
MX8000-IDT	16	12	18	3
Siemens Healthcare				
Sensation 4	4	4 or 10	8 or 15	2

Note—Only the American College of Radiology Imaging Network component of CT scanners was included in the table because dose measurement data were not available for Lung Screening Study component until 2004. For a few CT scanner models, a choice of detector configuration (4 × 1 mm or 4 × 2.5 mm) and table speed (8 or 15 mm/rotation) was provided for the trial sites.

the measurement and analysis presented here is the machine-specific parameter of normalized CTDI$_w$, or CTDI$_w$ on a per mAs basis, for each MDCT model used in the trial. By definition, normalized CTDI$_w$ excludes mAs and pitch and, therefore, reflects the characteristics of a particular scanner model independently of user technique preferences.

Four questions were addressed by statistical analysis of the CT dose measurement data. Were there statistically significant differences in normalized dose index by manufacturer? Were there statistically significant differences in normalized dose index by CT scanner model from a single manufacturer? Were there statistically significant differences in normalized dose index among all models and all manufacturers? Were there statistically significant differences in normalized dose index by increasing level of technology, as described by the number of data channels on the scanners? (To answer the final question, scanners were divided into two groups—early designs and more advanced designs. The early design group included scanners with four or eight data channels, and the more advanced design group included scanners with 16 or more data channels.)

Because of the extreme outliers, even after log-transforming the CTDI$_w$/mAs values, Huber's robust regressions were applied for all four questions [5]. A hierarchic modeling approach (STATA version 9.0 SE, StataCorp) was used to address the first three questions [6]. The hierarchic structure of a manufacturer and scanner models within a manufacturer was embedded in the statistical hierarchic modeling approach in that the covariates for CT models were nested in the covariates for the corresponding CT manufacturers. The covariates for CT manufacturer were used to address the first question, and the covariates for CT models nested in CT manufacturer were used to address the second question in a single analysis. To test the differences in the dose among all models and all manufacturers, multiple comparisons with Bonferroni adjusted p values were performed where the previous hierarchic modeling yielded a statistically significant difference. For the last question, to test the difference in the dose by the number of data channels on the scanner, the robust regression was used. More details regarding the statistical modeling can be found in Appendix 1.

Results

A total of 221 CT dose measurements obtained on 96 MDCT scanners were included for analysis. The CT scanner technology present at the trial initiation was limited to scanners with four data channels, but by the end of the study, a wide variety of scanner models and technology had been included (Fig. 2 and Tables 2 and 3). Note that these results were compiled before any measurement exclusion to more completely describe the scanners used during the National Lung Screening Trial image collection phase.

The mean CTDI$_w$/mAs value obtained at 120 kVp was 0.096 mGy/mAs. Overall results by scanner manufacturer and model are shown in Table 4. The four questions addressed by the analysis are discussed in this section.

Were There Statistically Significant Differences in Normalized Dose Index by Manufacturer?

A statistically significant difference was found among manufacturers for normalized CTDI$_w$. The normalized CTDI$_w$ was significantly different for GE Healthcare versus Philips Healthcare ($p < 0.001$). The normalized CTDI$_w$ was not significantly different for GE Healthcare versus Siemens Healthcare ($p = 0.131$). The normalized CTDI$_w$ was significantly different for GE Healthcare versus Toshiba ($p < 0.001$). The normalized CTDI$_w$ was significantly different for Philips Healthcare versus Siemens Healthcare ($p < 0.0022$). The normalized CTDI$_w$ was significantly different for Philips Healthcare versus Toshiba ($p < 0.0001$).

TABLE 3: Fleet of CT Scanners Near Termination Date of Lung Screening Phase of the National Lung Screening Trial, as of December 31, 2006

Manufacturer, Model	No. of Data Channels	Beam Width Used (mm)	No. of Scanners in National Lung Screening Trial
GE Healthcare			
QX/i	4	10	11
LightSpeed Plus	4	10	9
LightSpeed Ultra	8	10	7
LightSpeed 16	16	20	23
VCT	64	40	1
Philips Healthcare			
MX8000	4	4 or 10	6
MX8000-IDT	16	12	2
Brilliance 64	64	40	1
Siemens Healthcare			
Sensation 4 Volume Zoom	4	4 or 10	14
Sensation 16	16	12	13
Sensation 64	32	19.2	2
Toshiba			
Aquilion 4	4	8	4
Aquilion 16	16	32	3

Note—Table includes scanners in both American College of Radiology Imaging Network and Lung Screening Study components of the screening study, but does not include scanners used at voltages other than 120 kVp exclusively for the National Lung Screening Trial.

The normalized $CTDI_w$ was significantly different for Siemens Healthcare versus Toshiba ($p < 0.0001$). The normalized $CTDI_w$ mean values and SDs are plotted in Figure 3.

Were There Statistically Significant Differences in Normalized Dose Index by CT Scanner Models Within a Single Manufacturer?

There were statistically significant differences in $CTDI_w$/mAs among different scanner models manufactured by GE Healthcare. The LightSpeed QX/i and LightSpeed 16 were different from the other three models ($p = 0.011$). The LightSpeed Ultra was different from LightSpeed 16 or LightSpeed Plus ($p = 0.022$). There were statistically significant differences in $CTDI_w$/mAs by Siemens Healthcare models. The Sensation/Volume Zoom 4 was different from Sensation 16 and 64 models ($p = 0.002$ and $p = 0.023$, respectively). There was a statistically significant difference in $CTDI_w$/mAs between Philips Healthcare models. The MX8000 (four channels) was different from the MX8000-IDT (16 channels) ($p = 0.001$). No significant difference was observed among Toshiba models, probably because of the small number of observations available (Table 3).

Were There Statistically Significant Differences in Normalized Dose Index Among All Models and All Manufacturers?

There were statistically significant differences in $CTDI_w$/mAs among models: Sensation 16 was different from LightSpeed QX/i ($p = 0.0318$) and MX8000-IDT ($p < 0.0001$). LightSpeed Ultra was different from MX8000-IDT ($p = 0.0020$). These results are shown in Figure 4.

Were There Statistically Significant Differences in Normalized Dose Index by Increasing Level of Technology, as Described by the Number of Data Channels on the Scanners?

Robust regression analysis showed that $CTDI_w$/mAs values measured on scanners with four or eight channels was significantly different than $CTDI_w$/mAs values from 16-, 32-, or 64-channel scanners, even after controlling for manufacturer ($p < 0.001$). These results are shown in Figure 5.

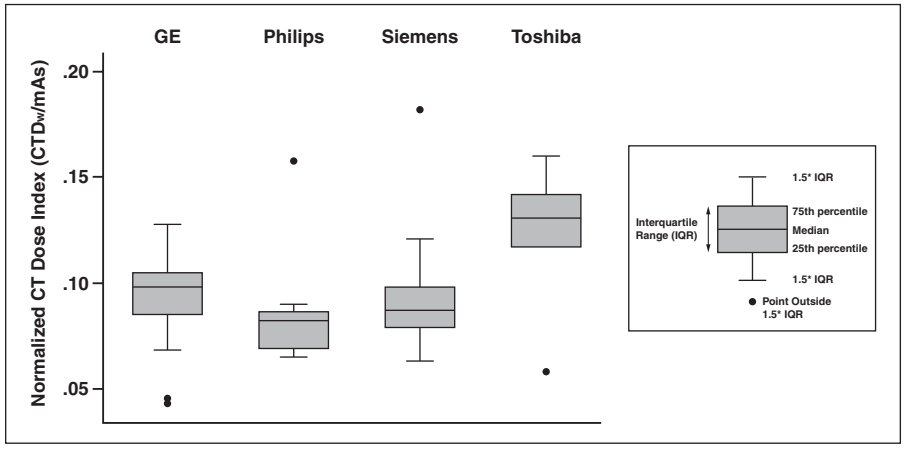

Fig. 3—Normalized dose results by manufacturer. Results were significantly different ($p < 0.0001$) by manufacturer. $CTDI_w$ = weighted CT dose index, mAs = milliampere-second.

Discussion

Examination of these figures reveals varying levels of consistency for normalized dose ($CTDI_w$/mAs) reported by sites with the same model of CT scanner. This value would be expected to be very consistent. Two independent factors could influence the disparate values. First, some scanners could be behaving differently from others of the same model. Second, there could have been some error or inconsistency in the measurement process or reporting procedures. Thus, the variation among scanners of the same model could be real, could be due to measurement variability, or (more likely) could be due to a combination of these two factors. (The large SDs observed for Philips Healthcare and Toshiba scanner models may be due to a combination of a small number of scanners and the relative unfamiliarity of physicists testing those scanners and cannot be interpreted with great confidence.)

The values reported in this article are reasonably consistent with those available from the ImPACT CT Patient Dosimetry Calculator (ImPACT Group; www.impactscan.org),

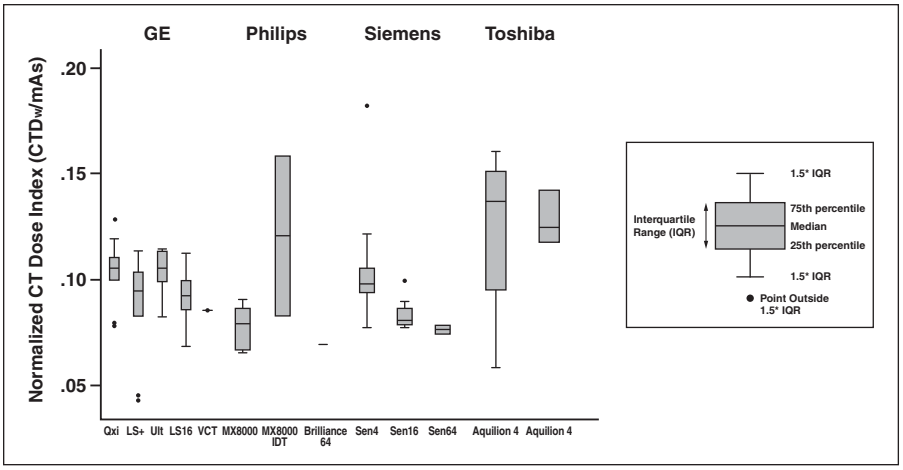

Fig. 4—There were statistically significant differences in normalized dose across manufacturers and models. $CTDI_w$ = weighted CT dose index, LS16 = LightSpeed 16, LS+ = LightSpeed Plus, mAs = milliampere-second, Sen = Sensation, Ult = Ultra.

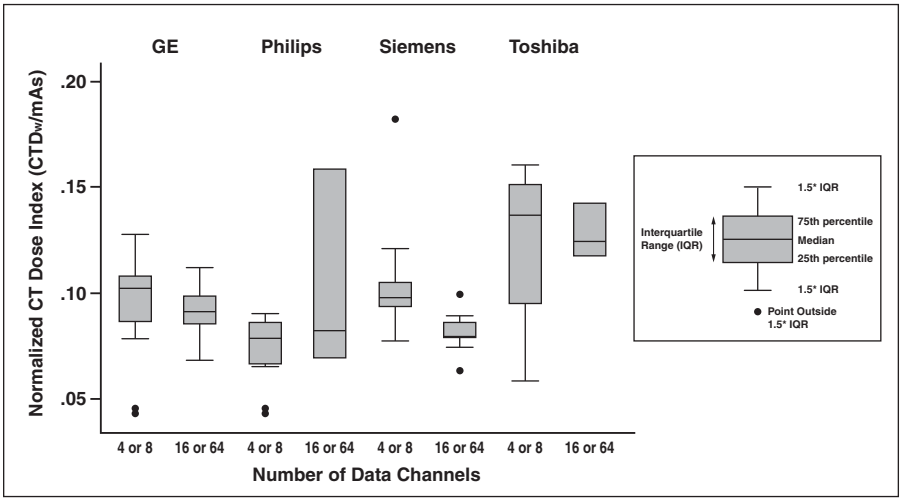

Fig. 5—Normalized dose measured on scanners with four or eight channels was significantly different than that for 16-, 32-, or 64-channel scanners, even after controlling for manufacturer ($p < 0.001$). Note that 32-channel Siemens Healthcare Sensation 64 scanners were included in "16 or 64" channel scanner group for simplicity. $CTDI_w$ = weighted CT dose index, mAs = milliampere-second.

which reports CT dose index values for many different CT scanners. The mean values reported in Table 4 agree with the values reported by the ImPACT Group to within 10% for seven of the 13 models listed, with four additional scanners having differences between 10% and 15% and only one scanner (MX8000-IDT, Philips Healthcare) reporting larger differences; this last scanner also had one of the larger SDs in our study. In addition, data from one of the more recently introduced scanners, the Philips Healthcare Brilliance 64 (of which there was only one in the National Lung Screening Trial), were not available from ImPACT. The data presented here represent measured values from a number of different sites and from several different scanners of the same make and model and, thus, may represent the range of measurement variation due to both measurement variation and scanner variation.

From the data shown in Figures 4 and 5, we can readily appreciate that the evolving technology with more data channels did not result in noticeably higher doses per mAs. In fact, it appears that the more advanced technology was associated with a consistently lower normalized dose measurement, which is indicative of greater dose efficiency. This result could be due to fewer overlap regions between successive dose profiles that results from the wider total x-ray beam collimations available in some newer scanner models, as well as to improvements in the scanner software.

It is important to appreciate the incorporation of more advanced technology as the National Lung Screening Trial progressed (Fig. 2 and Tables 2 and 3). From trial initiation through completion, the increased speed of the scanners required shorter and shorter breathholds. The increased complexity of the scanner acquisition parameters required additional physics oversight as the trial progressed.

Normalized dose varied among all scanners by a factor of almost two (minimum, 0.070 mGy/mAs; maximum, 0.127 mGy/mAs). Please note, however, that the minimum value of 0.07 mGy/mAs was recorded from a single measurement session on a single scanner.

$CTDI_{vol}$ (which is defined as $CTDI_w$ divided by pitch, to account for a pitch greater or less than unity) was not analyzed for this manuscript. The authors elected to examine $CTDI_w$ instead of $CTDI_{vol}$ to present data describing machine-specific dose, independent of pitch, which is a user-selected parameter. (For future estimations of population dose, the effect of pitch will have to be explicitly included.)

It should be noted that, at the time of this study, there was no DICOM standard widely available for several key values to determine radiation dose performance, such as pitch, total beam collimation, rotation time, and table feed. These values have since been incorporated into the DICOM standard (Enhanced CT DICOM object module) and are starting to be implemented by the CT manufacturers. The widespread implementation of these fields will make estimation of radiation dose performance easier and more accurate in the future.

This study of scanner performance represents exclusively dose values that were measured and reported. Although the Lung Screening Study and American College of Radiology Imaging Network investigators performed independent visual image quality assessments, such image quality metrics were not factored into these data. It is unknown whether the scanners that delivered relatively higher dose using the technique charts developed for this trial obtained relatively better image quality.

What can be inferred from these data is that mAs alone cannot be used as a universal indicator of image quality, such as noise, or even machine output, because radiation output per mAs varies between scanner manufacturers and models. As radiation dose becomes an increasingly important factor in radiology, the need to collapse many technical factors down to one or two to gain a clearer understanding of the long-term effects also increases. Unfortunately, this study indicates that simplifying image quality or noise on

TABLE 4: Normalized Dose Values Averaged by CT Scanner Manufacturer and Model

Manufacturer, Model	No. of Scanners	No. of CT Dose Index Measurements	Normalized Weighted CT Dose Index (mGy/mAs), Average (SD)
GE Healthcare			
QX/i	11	26	0.10 (0.015)
LightSpeed Plus	9	22	0.09 (0.025)
LightSpeed Ultra	7	23	0.10 (0.011)
LightSpeed 16	23	51	0.09 (0.011)
VCT	1	2	0.09 (—)
Philips Healthcare			
MX8000	6	13	0.08 (0.010)
MX8000-IDT	2	7	0.12 (0.053)
Brilliance 64	1	1	0.07 (—)
Siemens Healthcare			
Sensation 4 Volume Zoom	14	35	0.10 (0.025)
Sensation 16	13	25	0.08 (0.008)
Sensation 64	2	4	0.08 (0.002)
Toshiba			
Aquilion 4	4	6	0.12 (0.045)
Aquilion 16	3	6	0.13 (0.013)

Note—Overall average normalized dose (weighted CT dose index per milliampere-second) for all scanners operated at 120 kVp was 0.096 mGy/mAs. Data collected from scanners operated at other than 120 kVp for National Lung Screening Trial were not included in these values. Dashes indicate too few data points to compute a standard deviation value.

the basis of a mAs parameter is not likely to ultimately be useful because of the output variability among CT scanners.

Summary

A large collection of dose measurements was obtained on current vintage MDCT scanners during a multisite lung screening research trial. These dose measurements ($CTDI_w$) were normalized and reported on a per mAs basis, by CT scanner model.

This study found a statistically significant difference in normalized CT dose index among CT scanner manufacturers, likely because of design differences, such as filtration, bow-tie design, and geometry. Our findings also indicated a statistically significant difference in normalized CT dose index among CT scanner models manufactured by GE Healthcare, Siemens Healthcare, and Philips Healthcare. We also found a statistically significant difference in normalized CT dose index among all models and all manufacturers. Finally, we found a statistically significant difference in normalized CT dose index from CT scanners among manufacturers when we grouped them by number of data channels (four or eight data channels vs 16, 32, or 64 channels), suggesting that more complex scanners show improved dose efficiency. The average normalized CT dose index values varied by a factor of almost two across all scanners from all manufacturers. This study was focused on machine-specific normalized CT dose index, which is one of many factors that influence image quality and patient dose.

Acknowledgments

We thank medical physicists, research assistants, and technologists who made all the measurements. Without their contribution, this study would not have been possible.

References

1. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Report, Annex D: medical radiation exposures. New York, NY: United Nations, 2000
2. Cagnon CH, Cody DD, McNitt-Gray MF, Seibert JA, Judy PF, Aberle DR. Description and implementation of a quality control program in an imaging based clinical trial. *Acad Radiol* 2006; 13:1431–1441
3. McNitt-Gray MF. AAPM/RSNA Physics tutorial for residents: topics in CT—radiation dose in CT. *RadioGraphics* 2002; 22:1541–1553
4. Shope TB, Gagne RM, Johnson GC. A method for describing the doses delivered by transmission x-ray computed tomography. *Med Phys* 1981; 8:488–495
5. Huber PJ. Robust regression: asymptotics, conjectures, and Monte Carlo. *Ann Stat* 1973; 1:799–821
6. Gelman A, Hill J. *Data analysis using regression and multilevel/hierarchical models.* New York, NY: Cambridge University Press, 2007

APPENDIX 1: Statistical Modeling

A hierarchic modeling with robust regression was used to simultaneously address the first three questions: first, difference among manufacturers in normalized $CTDI_w$; second, difference among scanner model within a manufacturer in normalized $CTDI_w$; and third, difference among all models and all manufacturers in normalized $CTDI_w$. The hierarchic structure of a manufacturer (level 1) and scanner models within a manufacturer (level 2) were embedded within the statistical hierarchic modeling. In the first hierarchic structure, four manufacturers were coded as three dichotomized covariates to compare normalized $CTDI_w$ across manufacturers. In the second hierarchic structure, CT scanner models were nested within the CT manufacturers. They were coded as dichotomized variables to compare normalized $CTDI_w$ within the manufacturer. The regression equation is as follows:

$$\text{Log(normalized } CTDI_w) = \sum \text{Manufacturer} + \sum \text{CT scanner model| manufacturers} + \text{error term}$$

The third hypothesis of difference among all models and all manufacturers in normalized $CTDI_w$ was tested using Bonferroni's multiple comparisons from postestimation of the regression. The Bonferroni method was implemented conservatively, preventing us from finding false-positive differences in normalized $CTDI_w$. By combining two levels of hierarchic structure into one regression, the three hypotheses were able to be addressed.

The regression model for the last hypothesis, which is to test the difference in normalized $CTDI_w$ by the number of data channels on the scanner with covariates of manufacturers, is as follows:

$$\text{Log(normalized } CTDI_w) = \sum \text{Manufacturer} + \sum \text{Channels} + \text{error term}.$$