Comparison of radiation dose and imaging performance for the standard Toshiba x-ray tube and the Richardson Healthcare ALTA-750 replacement tube for the Toshiba Aquilion CT scanners.

by

Robert L. Dixon, Ph.D., FACR, FAAPM
President, Radiological Physics Consultants, Inc.
Professor Emeritus, Dept of Radiology
Wake Forest University School of Medicine
Winston-Salem, NC
Designated US CT Expert
IEC 62B MT30 CT Committee
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I. Methodology

On April 9, 10 we visited the Richardson Healthcare service training facility in Fort Mill , SC which has a Toshiba Aquilion-64 CT scanner in which a new standard Toshiba CXB-750D/4A (S/N 86195-Q7) x-ray tube was installed for our testing purposes and a service calibration performed.
After making a series of measurements with the Toshiba tube, the tube was replaced with a new Richardson Electronics ALTA-750 replacement tube from the factory (S/N ABD002H). After installation and re-calibration, the measurements were repeated. In short, same Aquilion-64 CT scanner, same dosimetry system – two different x-ray tubes.
(These dose results should also apply to the Aquilion-16 and 32 scanners since the same x-ray tube is used therein and the same Toshiba Dose specifications apply.)

II. Measurements

Radiation Dose: The same set of measurements were made on both tubes to compare the radiation dose delivered (CTDI) for a series of techniques specified by Toshiba for acceptance testing as outlined below.
Image performance: A complete American College of Radiology (ACR) accreditation test was run on the scanner for both the Toshiba and Richardson

tubes which includes additional dose measurements for typical clinical techniques. A separate resolution test was also performed.

Radiation Dose Results

Table I. $CTDI_{100}$ Measured Dose Values at Toshiba specifications technique 120 kVp, 100 mA, 1 sec, 4 x 4mm (16 mm slice) Toshiba Aquilion – 64 CT Scanner

	Toshiba tube $CTDI_{100}$ (mGy)		Richardson Tube $CTDI_{100}$(mGy)		Toshiba Specs (± 20%) $CTDI_{100}$ (mGy)	
Phantom	**Center**	**Periphery**	**Center**	**Periphery**	**Center**	**Periphery**
Head (16 cm)	**19.13**	**20.72**	**19.16**	**23.2**	**18.45**	**21.5**
Body (32 cm)	**7.08**	**15.74**	**7.16**	**15.2**	**6.57**	**14.57**

Conclusion: Both tubes deliver a value of $CTDI_{100}$ to within 10% of the Toshiba Specifications shown above for the standard technique - well within the ± 20 % Toshiba tolerance. For the more-reliable phantom center measurements, the Toshiba and Richardson tubes delivered the same dose within 1% of each other.

Measured CTDIvol values

The more common representation of "CT dose" (see Appendix) is CTDIvol which represents a weighted average of the central and peripheral axis $CTDI_{100}$ values and which is displayed on the CT monitor for the scan technique used, namely

$$CTDIvol = (1/3)CTDI_{100}(center) + (2/3)\ CTDI_{100}(periphery)$$

Table II. $CTDI_{vol}$ Measured Dose Values in mGy at Toshiba specifications technique

Toshiba Aquilion -64 CT

Phantom	Toshiba tube CTDIvol	Richardson Tube CTDIvol	Monitor Displayed CTDIvol	Toshiba Specs (± 20%) CTDIvol
Head (16 cm)	**20.19**	**21.85**	**20.5**	**16.4 - 24.6 Midrange 20.5**
Body (32 cm)	**12.86**	**12.49**	**12.1**	**9.7 - 14.5 Midrange 12.1**

<u>Conclusion</u>: Both Toshiba and Richardson tubes deliver a value of CTDIvol to within 3% of each other for the body phantom and within 8% for the head phantom, and both are well-within the Toshiba Specifications shown above for the standard technique, namely easily within the ± 20 % Toshiba tolerance range shown above.

The agreement with the displayed CT console CTDIvol value for the body phantom is within 6% for the Toshiba tube, and within 3% for the Richardson tube. Likewise for the head phantom, the agreement is within -1.5 % and +7% for the Toshiba and Richardson tubes, respectively.

The dose (CTDI) also depends on other factors, most notably the detector acquisition configuration which affects the z – collimator aperture (actual beam width). The actual beam width is larger than the nominal width (over-beaming) which increases the dose significantly for narrow beams. The tube voltage (kV) obviously affects the dose. Measurements for these dose adjustment factors for both tubes are given below.

Table III. Measured Aperture Dose Adjustment Factors for $CTDI_{100}$

(Body Phantom Center)

Nominal Collimator setting	Toshiba Tube	Richardson Tube	Toshiba Specifications
8x4mm (32 mm)	0.93	0.92	0.97
4x4mm (16 mm)	1.00	1.00	1.00
1x1mm (1 mm)	3.72	3.72	3.8

<u>Conclusion</u>: Dependence of $CTDI_{100}$ on z-collimator aperture is essentially the same for both Toshiba and Richardson tubes and in good agreement with published Toshiba specifications.

The measured values are also consistent with our actual beam width measurements of 36mm, 19mm, and 4 mm for both tubes[7] (see CTDI-aperture, Dixon et al. Medical Physics 32(12)2005).

Table IV. Measured kV dose adjustment factors (peripheral axis body)

kV	Toshiba tube	Richardson tube	Toshiba Spec
80	0.38	0.39	0.39
120	1.000	1.000	1.00
135	1.27	1.27	1.27

<u>Conclusion</u>: Near-perfect agreement with kVp variation between Toshiba and Richardson Tubes as would be expected (same scanner) as well as with Toshiba specifications.

AMERICAN COLLEGE OF RADIOLOGY (ACR) ACCREDITATION TESTS

A complete ACR accreditation test was performed for both the Toshiba and Richardson tubes – the same required ACR accreditation tests which we perform for our Aquilion-equipped client hospitals and clinics.

Typical Image Acquisition Technical Parameters

	Adult Head	Adult Abdomen	Pediatric Head	Pediatric Abdomen	Hi Res Chest
kVp	120	120	120	120	120
mA	220	200	150	100	150
Time per rotation (sec)	0.75	0.50	0.50	0.50	0.50
mAs	165	100	75	50	75
effective/displayed mAs	251	121	114	59	90
Scan FOV (cm)	24	50	24	24	50
Display FOV (cm)	22	36	20	22	36
Reconstruction Algorithm	FC 23	FC 17	FC 47	FC 13	FC 86
Axial (A) or Helical (H)	H	H	H	H	H
# of data channels used(N)	32	64	32	32	64
Z-axis collimation (T, in mm)	0.5	0.5	0.5	0.5	0.5
A: Table increment (mm) or H: Table Speed (mm/rot) (I)	10.5	26.5	10.5	13.5	26.5
Pitch (P, = (I/(NxT)))	0.656	0.828	0.656	0.844	0.828
Reconstructed Scan Width (mm)	5.0	5.0	5.0	5.0	1.0
Reconstructed Scan Interval (mm)	5.0	5.0	5.0	5.0	10.0

Toshiba Tube

Displayed CTDIvol (mGy)	56.7	14.6	25.8	13.4	11.0
Measured CTDIvol (mGy)	54.4	15.5	25.4	14.0	N/A
% Difference	-4.06%	6.16%	-1.55%	4.48%	N/A

Richardson Tube

Displayed CTDIvol (mGy)	56.7	14.6	25.8	13.4	11.0
Measured CTDIvol (mGy)	57.8	15.2	27.4	14.5	N/A
% Difference	1.94%	4.11%	6.20%	8.21%	N/A

Contrast to Noise Ratio (CNR)

	Adult Head		Adult Abdomen		Pediatric Head		Pediatric Abdomen	
	Toshiba	Richardson	Toshiba	Richardson	Toshiba	Richardson	Toshiba	Richardson
Smallest Diameter Cylinders Visible (mm)	5	5	6	6	N/A	N/A	N/A	N/A
Mean CT Number Over 25 mm Cylinder (a)	90.5	91.9	92.6	92.1	91.7	93.0	90.6	93.4
Mean CT Number Next to 25 mm Cylinder (b)	83.8	85.2	86.0	86.2	85.2	86.7	84.2	85.8
Std Dev Next to 25 mm Cylinder (c)	3.8	3.6	5.3	4.9	7.8	7.5	9.3	11.2
CNR = (a-b)/c	1.76	1.86	1.25	1.20	0.83	0.84	0.69	0.68
CNR Pass Criterion	> 1.0		> 1.0		> 0.7		> 0.4	

The higher the CNR, the better. Both the Toshiba and Richardson tubes deliver quite comparable CNRs as shown above.

High Contrast (Spatial) Resolution

	Adult Abdomen		Hi Res Chest	
	Toshiba	Richardson	Toshiba	Richardson
Spatial Frequency Resolved (lp/cm)	7	7	10	10

*The ACR no longer evaluates spatial resolution for accreditation, however, in years past the Pass Criterion was $\geq$ 6 lp/cm for the Adult Abdomen and $\geq$ 8 lp/cm for the Hi Res Chest

Uniformity, Noise, and Artifact Evaluation (Using Adult Abdomen Series)

Location	Mean (HU)		Noise (Std Dev)		Uniformity (Center to Edge Difference)		
	Toshiba	Richardson	Toshiba	Richardson			
Center	0.40	0.30	4.90	5.30	Location	Toshiba	Richardson
3 o'clock	1.40	0.50	No Visible Artifacts	No Visible Artifacts	Center - 3 o'clock	1.00	0.20
6 o'clock	1.10	0.10			Center - 6 o'clock	0.70	0.20
9 o'clock	0.60	0.90			Center - 9 o'clock	0.20	0.60
12 o'clock	0.90	1.10			Center - 12 o'clock	0.50	0.80

Uniformity Pass Criterion: The center to edge difference (for each measurement location) must be within $\pm$ 5 HU. Differences between 5-7 HU will result in a minor deficiency. Differences of greater than 7 HU will result in a major deficiency. Both tubes were within 1 HU and easily pass. The difference in noise is trivial; moreover, it is the contrast-to-noise ratio shown above which is the more important parameter.

Beam Width Measurements

Detector Configuration	Toshiba	Richardson
1 x 1.0 mm	4.0	4.0
4 x 4.0 mm	19.0	19.0
8 x 4.0 mm	36.0	36.0

Conclusion (ACR testing): The doses (CTDIvol) delivered between the Toshiba and Richardson tubes were comparable to better than 6 % for the clinical techniques of Adult Head, Adult Abdomen, Pediatric Head, and Pediatric Abdomen. In the image quality arena, the Toshiba and Richardson tubes exhibited essentially equal image quality. The scanner easily met the ACR passing criteria with both tubes.

High Contrast Spatial Resolution Measurements

with high resolution reconstruction algorithms

1. Nuclear Associates phantom - 120 kVp, 200 mA, 1 sec,
   4 x 1.0mm, 2-stack, 100 mm FOV, FC 70 algorithm
   Toshiba Tube: 11 line-pairs/mm (0.45 mm)
   Richardson Tube: 11 line-pairs/mm (0.45 mm)
2. ACR phantom (Hi Res Chest technique – see ACR previous data page) FC-86 kernal
   Toshiba Tube: 10 line-pairs/mm
   Richardson Tube: 10 line-pairs/mm

Conclusion: A side-by-side comparison of the resulting phantom images showed no discernable difference in resolution between the Toshiba and Richardson tubes.

GLOBAL SUMMARY

The Toshiba and Richardson x-ray tubes exhibited comparable performance in the Toshiba Aquilion CT scanner in both the dose and image quality arenas. The doses (CTDIvol) delivered between the Toshiba and Richardson tubes were comparable to better than 6 % for the clinical techniques of Adult Head, Adult Abdomen, Pediatric Head, and Pediatric Abdomen in the ACR accreditation tests.
In the image quality arena, the Toshiba and Richardson tubes exhibited essentially equal performance in all ACR phantom tests (spatial resolution, contrast-to-noise ratio, uniformity, and freedom from artifacts). **This leads to the conclusion that a Richardson Electronics ALTA-750 replacement x-ray tube installed in a Toshiba Aqulion CT scanner would be indistinguishable from the standard Toshiba CXB-750D/4A tube insofar as the radiation dose delivered and imaging performance is concerned.**

On-site testing at Richardson Service Training Facility Fort Mill, SC performed by:

Robert L. Dixon, Ph.D.
Brian Stratmann, M.S.
Certified Radiological Physicists
(American Board of Radiology).

References

[1]R.L. Dixon et al. Report of AAPM Task Group 111 "Comprehensive methodology for the evaluation of radiation dose in x-ray computed tomography," American Association of Physicists in Medicine, College Park, MD, February 2010, http://www.aapm.org/pubs/reports/RPT_111.pdf.

[2]J.M. Boone et al. AAPM report # 204 Size-Specific Dose Estimates (SSDE) in Pediatric and Adult Body CT Examinations (Cross Reference: Report 220) http://www.aapm.org/pubs/reports/RPT_204.pdf

[3]R. L. Dixon and J. M. Boone, "Dose equations for tube current modulation in CT scanning and the interpretation of the associated CTDIvol," Med. Phys. 40, 111920 (14pp.) (2013).

[4]R. L. Dixon, "A new look at CT dose measurement: Beyond CTDI," Med. Phys. 30, 1272–1280 (2003).

[5]R. L. Dixon and J. M. Boone, "Analytical equations for CT dose profiles

derived using a scatter kernel of Monte Carlo parentage with broad applicability to CT dosimetry problems," Med. Phys. 38, 4251–4264 (2011).

[6]R. L. Dixon and J. M. Boone, "Cone Beam CT dosimetry: A unified and self-consistent approach including all scan modalities—With or without phantom motion," Med. Phys. 37, 2703–2718 (2010).

[7]R. L. Dixon, M. T. Munley, and E. Bayram, "An improved analytical model for CT dose simulation with a new look at the theory of CT dose," Med. Phys. 32, 3712–3728 (2005).

[8]R. L. Dixon and J. M. Boone, "Stationary table CT dosimetry and anomalous scanner-reported values of CTDIvol," Med. Phys. 41(1), 011907 (5pp.) (2014).

[9]R. L. Dixon and A. C. Ballard, "Experimental validation of a versatile system of CT dosimetry using a conventional ion chamber: Beyond CTDI100," Med. Phys. 34(8), 3399–3413 (2007).

[10]Dose equations for shift-Toshiba CT acquisition modes using variable pitch, tube current, and aperture, and the meaning of their associated CTDIvol
Robert L. Dixon, John M. Boone, and Robert A. Kraft
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Appendix: Primer on CT dose

The CT scanner does not report the actual dose to a given patient.
Although the value of the "dose-index" $CTDI_{vol}$ is directly associated with the CT scan performed on a particular patient (say John Smith), it represents the particular type of scan and technique factors used on Mr. Smith. However, its absolute value in mGy is not necessarily representative of the actual dose received by Mr. Smith, even though it may be recorded in his personal patient record. Rather, $CTDI_{vol}$ represents the dose that would be delivered to a 15 cm long plastic disk (phantom) of either 16 cm or 32 cm diameter (head or body) scanned at the same technique used on Mr. Smith, with the exception of the scan length. $CTDI_{vol}$ represents the dose for a scan length of only 100 mm, being calculated from $CTDI_{100}$. For automatic tube current modulation[3], $CTDI_{vol}$ is based on the average mA over the entire scan length *and* $CTDI_{100}$ (a bit of a disconnect[3])
For a body scan, the actual dose to a thin patient will be much larger than that for a thick patient for the same manual scan technique (kVp, mAs, $n \times T$, pitch, etc), whereas the reported value of $CTDI_{vol}$ is exactly the same for both. Thus the common value of $CTDI_{vol}$ reported by the scanner in mGy is not likely to represent the dose to either the thin or thick patient, but rather represents the dose to their dosimetry surrogate. Namely, a 32 cm diameter

plastic body phantom which is supposed to represent the body habitus of *every patient who gets a body scan*, whether thick or thin or whether receiving an abdomen or lung scan. The body phantom has no lungs.
That being said, the CT dose phantoms are intended to represent a *standard patient* insofar as dose is concerned; otherwise, why have both "head" and "body" phantoms? In fact, national surveys of CT dose to the population are based on using CTDI to represent the patient dose.
There is, however, a small subset of your patients for which $CTDI_{vol}$ is representive of the actual average dose across the central scan plane (for a 100 mm scan length). These are patients whose particular body circumference matches the attenuation and absorption of the 32 cm diameter plastic phantom (referred to hereinafter as *phantom doubles*). For an abdomen scan, a *body phantom double* would be a relatively large patient – roughly a 48" waist size. Since abdomen scans typically cover a length much greater than 100 mm, the actual patient dose would be about 20 % larger than $CTDI_{vol}$ even for a perfect *phantom double*. The variation in head circumference of the patient population is typically smaller – a *head phantom double* would wear a size 7½ hat. There is a correction to $CTDI_{vol}$ for patient size called $SSDE$[2] (Size Specific Dose Estimate) but this is not currently reported by CT scanners (see ref. 2 for details).

The primary use of $CTDI_{vol}$ is therefore not as an absolute patient dose to the patient being scanned, but rather as a relative dose indicator – to assist the CT operator in evaluating the relative dose implications of various choices of CT scan parameters available, and thus to avoid the often unnecessary use of high dose techniques. That is, the value of $CTDI_{vol}$ is displayed on the CT operators' console after setting up a scan technique, *and before initiating the scan*, so it behooves the operator to be familiar with typical values of $CTDI_{vol}$ for routine scan techniques in order to recognize an "outlier" [the ACR lists such "reference levels" for a few procedures].
Although the reported dose $CTDI_{vol}$ is by inference directly associated with an individual patient, it is a very crude measure of the actual dose to that patient, so its absolute value is of secondary importance in that regard.
However, the value of $CTDI_{vol}$, together with other patient-specific information, may be quite useful to the medical physicist in reconstructing a more accurate (albeit still *approximate*) patient dose when such a dose reconstruction is specifically requested. An example would be computing a fetal dose for a pregnant patient receiving a CT scan.
The CTDI paradigm does not apply for multiple, or single, axial rotations about a stationary phantom (such as brain perfusion studies in the cine mode[8]); hence the value of $CTDI_{vol}$ reported by the scanner is not representative of the dose – even to a *phantom double*.
DLP (Dose-Length-Product) is the other dose-related parameter reported

by the scanner (in mGy.cm) which value is a measure of the total energy deposited in the phantom (and not in the patient) by the scan technique used on the patient, and is based on $CTDI_{vol}$. As such, it is not further affected by the particular x-ray tube beyond the previously discussed effect on the value of $CTDI_{vol}$, and needs no further consideration in this document.
If $CTDI_{vol}$ is accurate then DLP will likewise be accurate.

However, our goal is quite specific and is unaffected by the vagaries of the CT dose reporting system described above.
In this study we are testing a *replacement tube* which is specifically designed to *emulate the Toshiba tube* it is replacing. Our dosimetric goal is merely to verify the consistency of the dose delivered (CTDI) using the Richardson replacement tube with that of the Toshiba tube it replaces.

TOSHIBA DOSE SPECIFICATIONS: These are described only as *typical dose values* about which an *expected deviation* of ±20 % from one Toshiba scanner to another can be anticipated (all equipped with the same model x-ray tube).