Technical Note: Precision and accuracy of a commercially available CT optically stimulated luminescent dosimetry system for the measurement of CT dose index

Thomas J. Vrieze
Department of Radiology, Mayo Clinic, Rochester, Minnesota 55905

Glenn M. Sturchio
Department of Medicine, Mayo Clinic, Rochester, Minnesota 55905

Cynthia H. McCollough[a)]
Department of Radiology, Mayo Clinic, Rochester, Minnesota 55905

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Purpose: To determine the precision and accuracy of $CTDI_{100}$ measurements made using commercially available optically stimulated luminescent (OSL) dosimeters (Landaur, Inc.) as beam width, tube potential, and attenuating material were varied.
Methods: One hundred forty OSL dosimeters were individually exposed to a single axial CT scan, either in air, a 16-cm (head), or 32-cm (body) CTDI phantom at both center and peripheral positions. Scans were performed using nominal total beam widths of 3.6, 6, 19.2, and 28.8 mm at 120 kV and 28.8 mm at 80 kV. Five measurements were made for each of 28 parameter combinations. Measurements were made under the same conditions using a 100-mm long CTDI ion chamber. Exposed OSL dosimeters were returned to the manufacturer, who reported dose to air (in mGy) as a function of distance along the probe, integrated dose, and $CTDI_{100}$.
Results: The mean precision averaged over 28 datasets containing five measurements each was 1.4% ± 0.6%, range = 0.6%–2.7% for OSL and 0.08% ± 0.06%, range = 0.02%–0.3% for ion chamber. The root mean square (RMS) percent differences between OSL and ion chamber $CTDI_{100}$ values were 13.8%, 6.4%, and 8.7% for in-air, head, and body measurements, respectively, with an overall RMS percent difference of 10.1%. OSL underestimated $CTDI_{100}$ relative to the ion chamber 21/28 times (75%). After manual correction of the 80 kV measurements, the RMS percent differences between OSL and ion chamber measurements were 9.9% and 10.0% for 80 and 120 kV, respectively.
Conclusions: Measurements of $CTDI_{100}$ with commercially available CT OSL dosimeters had a percent standard deviation of 1.4%. After energy-dependent correction factors were applied, the RMS percent difference in the measured $CTDI_{100}$ values was about 10%, with a tendency of OSL to underestimate CTDI relative to the ion chamber. Unlike ion chamber methods, however, OSL dosimeters allow measurement of the radiation dose profile. © *2012 American Association of Physicists in Medicine*. [http://dx.doi.org/10.1118/1.4754591]

Key words: computed tomography (CT), CT dose index, optically stimulated luminescence, radiation dosimetry, radiation dose profile

I. INTRODUCTION

Optically stimulated luminescence (OSL) is a phenomenon in which optical energy is used to stimulate the emission of light (i.e., luminescence) from a substance, some amount of time after that substance has absorbed energy from an external source.[1,2] OSL materials, similar to thermally stimulated luminescent materials, have applications in radiation dosimetry.[3–5] An in-depth description of OSL technology and an overview of the history of OSL are available elsewhere.[6,7] The widespread use of AL_2O_3:C for radiation dosimetry purposes was facilitated by its commercialization by Landauer, Inc.

The use of OSL material to measure the dose profiles from CT scanners has been previously described.[8,9] In these studies, the OSL strips and acrylic holders were manually prepared from Al_2O_3:C powder provided by Landauer, Inc. (Glenwood, IL) that had been incorporated onto a plastic strips, and the strips read out using a prototype reader that stimulated the strips with green light-emitting diodes. A slit was used to collimate the detected OSL emission light, providing spatial encoding of the dose as the strip was translated through the reader. The accuracy and precision of this system, as well its energy dependence, was measured for multidetector-row CT.[8,9] However, to the best of our knowledge, information regarding the accuracy, precision, and energy dependence of a commercially available OSL CT dosimetry system has not been reported. Thus, the purpose of this study was to evaluate the accuracy and precision of $CTDI_{100}$ measurements made using a commercially available OSL CT dosimetry system (Landaur, Inc.), relative to CTDI ion chamber measurements, as the radiation beam

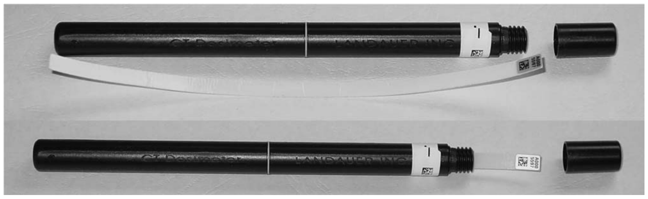

FIG. 1. CT OSL dosimeters (16-cm long) with caps removed. Top: Strip of plastic substrate coated with the OSL material (Al_2O_3:C) removed from tube. Bottom: OSL strip mostly inserted in tube.

width, x-ray tube potential, and scattering environment were varied.

II. MATERIALS AND METHODS

Landauer, Inc. CT OSL dosimeters were used in this evaluation. These dosimeters consisted of a 16-cm long light-tight plastic tube that contained a thin plastic substrate coated with the OSL material (Al_2O_3:C) (Fig. 1). Each dosimeter was exposed to the radiation produced by a single rotation, stationary CT scan (a single axial scan). Exposures were performed using a Somatom Definition DS (Siemens Healthcare, Forchheim, Germany) and subsequently returned to the manufacturer (Landauer, Inc.) for analysis.

Measurements were obtained in six attenuation geometries: the probe at isocenter in (1) the absence of any phantom attenuation, (2) the center of a 16-cm acrylic cylinder, and (3) in the center of a 32-cm acrylic cylinder. The dosimeter was positioned with the longitudinal axis of the probe colinear with the axis of rotation of the CT system. The three remaining measurements were obtained with the probe placed to the right of isocenter (“3 o’clock position”); the probe was placed 7 cm to the right of isocenter in the absence of an attenuating phantom and in the 16-cm acrylic cylinder, and 15 cm to the right of isocenter in the 32-cm acrylic cylinder (Fig. 2). The center of the probe, along the z axis, was positioned in the center of the scan plane for all measurements.

Scans using nominal total beam widths of 3.6, 6.0, 19.2, and 28.8 mm and 120 kV potential were performed for each of the measurement geometries. No data were collected in the body CTDI phantom (32 cm diameter) using a total nominal beam width of 3.6 mm, as a body scan mode is not available for that beam width. An additional scan was obtained using a tube potential of 80 kV for all measurement geometries and a total nominal beam width of 28.8 mm.

Following the exposure of each CT OSL dosimeter, the probe was removed and a 100-mm long CTDI ionization

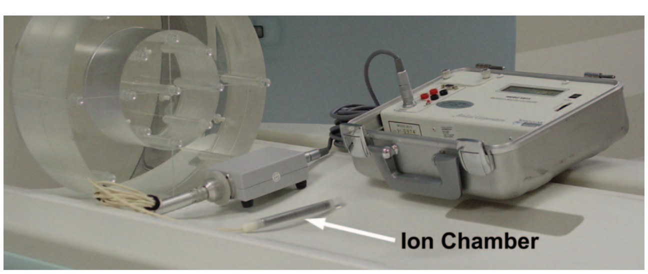

FIG. 2. Typical equipment used to measure $CTDI_{100}$: acrylic CTDI phantom, 100-mm long ionization chamber, and dosimeter control unit.

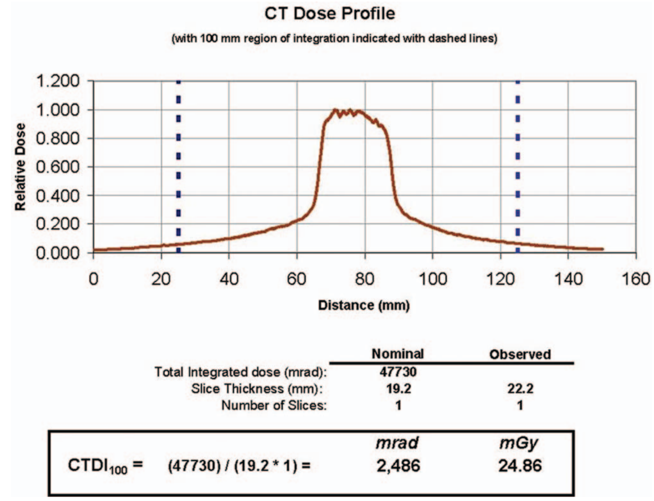

FIG. 3. Example of the CT dose profile report that is returned after the OSL strip is scanned by the manufacturer.

chamber (Model 10 × 5-3CT ion chamber and Model 9015 electrometer, Radcal Corporation, Monrovia, CA) was placed in the same position and exposed under the same experimental conditions.

Five measurements were made for each of the 28 parameter combinations. Ionization chamber measurements were converted to $CTDI_{100}$ values using the chamber and electrometer calibration values and an F-factor for air. The exposed OSL dosimeters were returned to the manufacturer, who reported dose-to-air (mGy) as a function of distance along the probe, integrated dose, and $CTDI_{100}$. Both electronic and hard-copy data were provided (Fig. 3). For each set of five measurements, the mean and standard deviation of the individual values were calculated.

The percent difference between the CT OSL and the CTDI ionization chamber measurements were calculated as the difference between the measurements normalized to the ionization chamber measurements:

$$\% \text{ difference} = \frac{M_{\text{OSL}} - M_{\text{ion chamber}}}{M_{\text{ion chamber}}} * 100\%.$$

Both the mean and the root mean square of the percent difference were calculated as a function of the attenuation geometry, nominal total beam width, and tube potential.

Initial results (not shown) demonstrated decreased agreement with ionization chamber measurements for lower tube potential settings (OSL over responded relative to ionization chamber measurements by as much as 27% at 80 kV). Subsequent discussions with the manufacturer resulted in the use of a multiplicative correction factor of 0.803 to all 80 kV OSL results and was provided by Landauer, Inc. and was applied to all 80 kV data reported here.

III. RESULTS

Tables I and II present the OSL and ion chamber $CTDI_{100}$ measurements for the center and 3 o’clock positions, respectively, as a function of attenuating geometry and beam width at 120 kV. Tables III and IV present the measurement results

TABLE I. Results of CT OSL and ion chamber $CTDI_{100}$ measurements for varied scattering materials and beam widths for a tube potential of 120 kV.

Scattering material	Beam width (mm)	Center position: OSL $CTDI_{100}$ (mGy)[a]	OSL coefficient of variation (%)	Ion chamber $CTDI_{100}$ (mGy)[a]	Ion chamber coefficient of variation (%)	Difference in mean $CTDI_{100}$ values (%)[b]
None (in air)	3.6	58.1 ± 0.7	1.1	63.7 ± 0.0	0.03	− 8.8
	6.0	34.6 ± 0.3	1.0	38.2 ± 0.0	0.09	− 9.2
	19.2	36.6 ± 0.4	1.0	41.0 ± 0.0	0.02	− 10.7
	28.8	33.7 ± 0.2	0.7	37.4 ± 0.0	0.09	− 9.9
16-cm CTDI head phantom	3.6	42.9 ± 1.2	2.7	40.6 ± 0.1	0.27	5.7
	6.0	26.8 ± 0.2	0.9	24.3 ± 0.0	0.20	10.2
	19.2	26.8 ± 0.3	1.1	26.0 ± 0.0	0.03	3.1
	28.8	24.4 ± 0.3	1.4	23.6 ± 0.0	0.05	3.6
32-cm CTDI body phantom	3.6	—	—	—	—	—
	6.0	9.2 ± 0.1	1.6	8.2 ± 0.0	0.21	11.5
	19.2	9.9 ± 0.2	1.7	8.9 ± 0.0	0.04	11.1
	28.8	8.9 ± 0.1	2.4	8.1 ± 0.0	0.07	10.4
Average % difference						1.5
Root mean square % difference						9.0

[a]Values are mean ± standard deviation. Standard deviation values less than 0.05 mGy were rounded to 0.0 mGy.
[b](OSL—ion chamber)/ion chamber × 100.

TABLE II. Results of CT OSL and ion chamber CTDI100 measurements for varied scattering materials and beam widths for a tube potential of 120 kV.

Scattering material	Beam width (mm)	3 o'clock position: OSL $CTDI_{100}$ (mGy)[a]	OSL coefficient of variation (%)	Ion chamber $CTDI_{100}$ (mGy)[a]	Ion chamber coefficient of variation (%)	Difference in mean $CTDI_{100}$ values (%)[b]
None (in air)	3.6	25.3 ± 0.3	1.23	31.4 ± 0.0	0.11	− 19.4
	6.0	15.2 ± 0.1	0.59	18.8 ± 0.0	0.04	− 18.9
	19.2	17.1 ± 0.3	1.47	20.2 ± 0.0	0.05	− 15.5
	28.8	15.9 ± 0.3	1.77	18.6 ± 0.0	0.10	− 14.4
16-cm CTDI head phantom	3.6	38.4 ± 0.2	0.64	39.8 ± 0.0	0.07	− 3.3
	6.0	22.6 ± 0.4	1.58	23.8 ± 0.0	0.07	− 5.0
	19.2	24.4 ± 0.6	2.55	25.5 ± 0.0	0.04	− 4.4
	28.8	22.0 ± 0.2	0.79	23.3 ± 0.0	0.08	− 5.5
32-cm CTDI body phantom	3.6	—	—	—	—	—
	6.0	15.1 ± 0.2	1.24	16.3 ± 0.0	0.06	− 7.4
	19.2	16.3 ± 0.2	1.14	17.4 ± 0.0	0.08	− 6.0
	28.8	15.1 ± 0.3	1.81	15.9 ± 0.0	0.05	− 5.0
Average % difference						− 9.5
Root mean square % difference						11.2

[a]Values are mean ± standard deviation. Standard deviation values less than 0.05 mGy were rounded to 0.0 mGy.
[b](OSL—ion chamber)/ion chamber × 100.

TABLE III. Results of CT OSL and ion chamber measurements of $CTDI_{100}$ for 120 kV and 80 kV beam potential and 24 × 1.2 mm beam collimation (28.8 mm nominal beam width).

Scattering material	Tube potential (kV)	Center position: OSL $CTDI_{100}$ (mGy)[a]	OSL coefficient of variation (%)	Ion chamber $CTDI_{100}$ (mGy)[a]	Ion chamber coefficient of variation (%)	Difference in mean $CTDI_{100}$ values (%)[b]
None (in air)	80	12.5 ± 0.3	1.86	14.1 ± 0.0	0.04	− 11.4
	120	33.7 ± 0.2	0.74	37.4 ± 0.0	0.09	− 9.9
16-cm CTDI head phantom	80	7.3 ± 0.1	0.91	7.8 ± 0.0	0.10	− 6.5
	120	24.4 ± 0.3	1.38	23.6 ± 0.0	0.05	3.6
32-cm CTDI body phantom	80	2.2 ± 0.0	1.14	2.3 ± 0.0	0.08	− 0.3
	120	8.9 ± 0.2	2.40	8.1 ± 0.0	0.07	10.4

[a]Values are mean ± standard deviation. Standard deviation values less than 0.05 mGy were rounded to 0.0 mGy.
[b](OSL—ion chamber)/ion chamber × 100.

TABLE IV. Results of CT OSL and ion chamber measurements of $CTDI_{100}$ for 120 kV and 80 kV beam potential and 24 × 1.2 mm beam collimation (28.8 mm nominal beam width).

		3 o'clock position				
Scattering material	Tube potential (kV)	OSL $CTDI_{100}$ (mGy)[a]	OSL coefficient of variation (%)	Ion chamber $CTDI_{100}$ (mGy)[a]	Ion chamber coefficient of variation (%)	Difference in mean $CTDI_{100}$ values (%)[b]
None (in air)	80	5.0 ± 0.1	2.17	5.9 ± 0.0	0.06	− 15.1
	120	15.9 ± 0.3	1.77	18.6 ± 0.0	0.10	− 14.4
16-cm CTDI head phantom	80	7.2 ± 0.1	1.41	7.8 ± 0.0	0.05	− 7.6
	120	22.0 ± 0.2	0.79	23.3 ± 0.0	0.08	− 5.5
32-cm CTDI body phantom	80	4.6 ± 0.1	1.17	5.2 ± 0.0	0.03	− 11.3
	120	15.1 ± 0.3	1.81	15.9 ± 0.0	0.05	− 5.0

[a]Values are mean ± standard deviation. Standard deviation values less than 0.05 mGy were rounded to 0.0 mGy.
[b](OSL—ion chamber)/ion chamber × 100.

at 80 and 120 kV for the 28.8 nominal beam width at the center and 3 o'clock position, respectively.

The root mean square percent differences in mean values between the OSL and ion chamber $CTDI_{100}$ values were 13.8% in air, 6.4% in the head phantom, and 8.7% in the body phantom. Using the manufacturer-supplied correction factor for 80 kV, the root mean square percent differences between the OSL and ion chamber measurements were 9.9% for 80 kV and 10.0% at 120 kV. Over all the measured data, the root mean square percent difference was 10.1%, with the OSL measurements underestimating $CTDI_{100}$ relative to the ion chamber measurements 75% (21/28) of the cases. Due to the order or magnitude higher coefficient of variation observed for OSL measurements relative to ionization chamber measurements, the uncertainty in the calculated percentage differences is essentially the same as the uncertainty in the OSL measurements.

The mean precision (% standard deviation) averaged over all 28 datasets ($n = 5$ measurements each) was 1.4% ± 0.6% (range = 0.6%–2.7%) for the OSL and 0.08% ± 0.06% (range = 0.02%–0.30%) for the ion chamber measurements.

IV. DISCUSSION

The energy-dependent response of the aluminum oxide-based OSL material makes the use of an energy-dependent correction factor necessary. The data reported by the manufacturer were initially not corrected for this energy dependence. While the data measured using 120 kV were in reasonable agreement with the ion chamber values, a correction factor of 0.803 was required in order to achieve reasonable accuracy at 80 kV. As this correction factor may not be automatically applied, it is imperative to determine from the manufacturer the value of the appropriate correction and whether the correction factor has been applied. Alternatively, users may perform calibration measurements using ionization chambers, which exhibit negligible energy dependence in the range of energies used in CT imaging.

The precision (standard deviation) of CTDI measurements made using the OSL dosimeters was approximately 1.4%, which is about 17.5 times larger than that measured using the CTDI ionization chamber (0.08%). However, this value is likely acceptable for measurement of $CTDI_{100}$. Using the CTDI ionization chamber as the reference standard, the inaccuracy (root mean square percent difference) of $CTDI_{100}$ values measured with OSL was about 10%, with a strong tendency of the OSL to underestimate $CTDI_{100}$ values. Yukihara *et al.* evaluated $CTDI_{100}$ values using noncommercial OSL strips and a prototype reader.[8] The precision of their triplicate measurements at four different geometries with tube potential at 120 kVp were similar to our findings, with a range from 0.6% to 3.7%. In that work, the authors applied calibration factors specific to the phantom size, position in the phantom, and tube potential, reporting that the $CTDI_{100}$ values determined using OSL strips and the ion chamber measurements agreed within ±5%.[8]

Pragmatically, we found the OSL dosimeters to be easy to use. The dosimeter is merely placed in the desired position, exposed to radiation, and returned to the manufacturer for analysis. For situations where ionization chamber and electrometer equipment is not readily available or practical (for example, for dose measurements on patients as part of multicenter trials), this may be a useful feature. Additionally, the unique property of the CT OSL dosimeter is the ability to provide high spatial resolution radiation dose profile information, as well as integrated dose. The dosimeters are limited, however, by the need to return the probe to the manufacturer for processing and the single-use nature of each unit. This differs from ionization chambers, which can be used repeatedly, with the results being immediately available to the user.

V. CONCLUSIONS

The precision (% standard deviation) of measurements of $CTDI_{100}$ made with CT OSL dosimeters is about 1.4%, which is about 17.5 times larger than that measured using a CTDI ion chamber (0.08%). This is likely acceptable for measurement of $CTDI_{100}$. Using the CTDI ion chamber as the gold standard, the inaccuracy (root mean square % difference) of $CTDI_{100}$ values measured with a commercially available CT OSL dosimetry system was about 10%, with a tendency of the OSL to underestimate dose CTDI values relative to the ion chamber. The energy-dependent response

of AL_2O_3:C necessitates careful attention to calibration for any parameters that could affect the beam spectrum interacting with the dosimeter, including the tube potential, phantom size, and composition, and even the position within the phantom. For the commercially available CT OSL dosimeter evaluated here, manual correction of the data at low kV settings (e.g., 80 kV) was required to achieve reasonable levels of accuracy (e.g., agreement between OSL and ion chamber measurements within about 10%). Unlike ion chamber methods, however, OSL dosimeters allow measurement of the radiation dose profile. Overall, with adequate calibration for the energy dependence of AL_2O_3:C, the commercially available CT OSL dosimeters evaluated here can provide reasonable accuracy and precision for the measurement of $CTDI_{100}$.

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[a]Author to whom correspondence should be addressed. Electronic mail: mccollough.cynthia@mayo.edu; Telephone: (507) 284-6875; Fax: (507) 284-2405.

[1]D. J. Huntley, D. I. Godfreysmith, and M. L. W. Thewalt, "Optical dating of sediments," Nature (London) **313**, 105–107 (1985).

[2]M. Akselrod and V. Kortov, "Thermoluminescent and exoemission properties of new high sensitivity TLD *-Al2O3:C crystals," Radiat. Prot. Dosim. **33**, 123–126 (1990).

[3]L. BotterJensen and S. W. S. McKeever, "Optically stimulated luminescence dosimetry using natural and synthetic materials," Radiat. Prot. Dosim. **65**, 273–280 (1996).

[4]B. G. Markey, L. E. Colyott, and S. W. S. McKeever, "Time-resolved optically stimulated luminescence from [alpha]-Al2O3:C," Radiat. Meas. **24**, 457–463 (1995).

[5]H. Nanto, K. Murayama, T. Usuda, S. Taniguchi, and N. Takeuchi, "Optically stimulated luminescence in Kcl-Eu single-crystals," Radiat. Prot. Dosim. **47**, 281–284 (1993).

[6]L. Boetter-Jensen, S. W. S. McKeever, and A. Wintle, *Optically Stimulated Luminescence Dosimetry* (Elsevier Science, Amsterdam, 2003).

[7]E. G. Yukihara and S. W. S. McKeever, *Optically Stimulated Luminescence: Fundamentals and Applications* (John Wiley & Sons, West Sussex, United Kingdom, 2011).

[8]E. G. Yukihara, C. Ruan, P. B. Gasparian, W. J. Clouse, C. Kalavagunta, and S. Ahmad, "An optically stimulated luminescence system to measure dose profiles in x-ray computed tomography," Phys. Med. Biol. **54**, 6337–6352 (2009).

[9]C. Ruan, E. G. Yukihara, W. J. Clouse, P. B. R. Gasparian, and S. Ahmad, "Determination of multislice computed tomography dose index (CTDI) using optically stimulated luminescence technology," Med. Phys. **37**, 3560–3568 (2010).