CHARACTERISATION OF ENERGY RESPONSE OF $\text{Al}_2\text{O}_3\text{:C}$ OPTICALLY STIMULATED LUMINESCENT DOSEMETERS (OSLDs) USING CAVITY THEORY

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Aluminium oxide ($\text{Al}_2\text{O}_3\text{:C}$) is a common material used in optically stimulated luminescent dosimeters (OSLDs). OSLDs have a known energy dependence, which can impact on the accuracy of dose measurements, especially for lower photon energies, where the dosimeter can overrespond by a factor of 3–4. The purpose of this work was to characterise the response of $\text{Al}_2\text{O}_3\text{:C}$ using cavity theory and to evaluate the applicability of this approach for polyenergetic photon beams. The cavity theory energy response showed good agreement (within 2 %) with the corresponding measured values. A comparison with measured values reported in the literature for low-energy polyenergetic spectra showed more varied agreement (within 6 % on average). The discrepancy between these results is attributed to differences in the raw photon energy spectra used to calculate the energy response. Analysis of the impact of the photon energy spectra versus the mean photon energy showed improved accuracy if the energy response was determined using the entire photon spectrum rather than the mean photon energy. If not accounted for, the overresponse due to photon energy could introduce substantial inaccuracy in dose measurement using OSLDs, and the results of this study indicate that cavity theory may be used to determine the response with reasonable accuracy.

INTRODUCTION

Optically stimulated luminescent dosimeters (OSLDs) have traditionally been used as personal dosimeters; however, these dosimeters have recently gained popularity in medical applications for monitoring and tracking patient dose. Owing to their small size, high sensitivity and ease of readability^(1–5), OSLDs are well suited to dose measurements in medical settings.

A common material for OSLDs is carbon-doped aluminium oxide ($\text{Al}_2\text{O}_3\text{:C}$). This crystal possesses inherent properties of both thermoluminescence and optically stimulated luminescence—both heat and light can be used to release electrons ‘trapped’ in the energy states between the conduction band and the valence band⁽⁵⁾. However, optical stimulation allows these dosimeters to be read at room temperature without the practical and technical difficulties associated with heating⁽⁵⁾. Also, dose information in $\text{Al}_2\text{O}_3\text{:C}$ is not lost after the initial read; OSLDs can be read multiple times with minimal signal loss. These advantages, as well as their relatively low cost, make this type of dosimeter an attractive option for many applications.

For accurate dosimetry, an energy correction specific to the irradiation energy is generally necessary. The energy correction factor depends on the irradiation photon energy spectrum and is derived from

the relative response (RR) of the dosimeter to a standard photon source. This correction is often assumed to be constant for the nominal irradiation energy, despite evidence that this may introduce additional uncertainties⁽⁶⁾. While the correction factor can be directly measured or calculated with Monte Carlo simulations, these approaches can be challenging and time-consuming. In principle, correction factors can also be calculated using cavity theory, which has been used, in previous studies, to determine the energy dependence of other solid-state detectors^(6–11). Burlin cavity theory is most appropriate for ‘medium-sized’ cavities, where the total dose is due to contributions from both photon and electron interactions inside the cavity^(8, 12). Cavities of varying physical size can thereby be well approximated using this theory. This calculation-based approach may provide a useful alternative method for determining energy correction factors without requiring detailed measurements or simulations.

Recent studies have evaluated the energy dependence of $\text{Al}_2\text{O}_3\text{:C}$ for discrete photon energies and beams^(2, 4, 13–15). Also, the response of $\text{Al}_2\text{O}_3\text{:C}$ as a thermoluminescent dosimeter has been evaluated for a range of photon energies^(16, 17). To the authors’ knowledge, the response of $\text{Al}_2\text{O}_3\text{:C}$ as a continuous function of photon energy has not previously been described using cavity theory. The objective of this

work, therefore, was to establish an expression for the energy response of $\text{Al}_2\text{O}_3\text{:C}$ OSLD, using Burlin cavity theory, which could be applied to any arbitrary photon spectrum. The energy response determined by means of cavity theory was evaluated through a comparison with the measured values for a range of irradiation conditions, using a typical medical radiotherapy photon beam. Furthermore, a comparison with the measured values reported in the literature was done for a range of common poly-energetic beams.

MATERIALS AND METHODS

The OSLDs evaluated in this study are Landauer nanoDots (Landauer, Inc., Glenwood, IL, USA), which are thin discs of a diameter of 4 mm and a thickness of 0.3 mm. The sensitive material is housed in a light-tight and tissue-equivalent plastic casing. The thickness of the casing is small (<1 mm) on both sides of the disc and was not considered in the energy response calculations because the composition is very close to that of the surrounding medium (water). These dots are commercially available and are currently the standard dosimeter for the remote dosimetry programme of the Radiological Physics Center (RPC, MD Anderson Cancer Center, Houston, TX, USA). The dosimeters were read using an InLight Microstar OSL reader (Landauer, Inc.), which was operated in continuous wave mode for a 7-sread time.

Calculation of dose to OSLDs using Burlin cavity theory

The OSLDs represent a cavity placed in a medium (water) as a means of measurement of the absorbed dose. Thus, cavity theory can be used to determine the energy dependence of the dosimeter theoretically, given the energy spectra of the photon beam incident on the OSLD. Cavity theory depends on the geometry of the cavity, particularly the mean path length through the cavity. The nanoDots used in this study are not spherical (as most readily described by cavity theory) but are instead a thin disc. Therefore, the cavity volume was approximated in three different ways to determine the dependence of the cavity theory on the size and geometry of the detector. The first approach (Model 1) estimated the OSLD disc as a sphere with a diameter equal to the thickness of the disc (0.3 mm); the second approach (Model 2) estimated it as a sphere with a volume equal to that of the disc; the third approach (Model 3) estimated it as a sphere with a radius equal to the radius of the disc (2 mm). The radius, volume and mean

Table 1. Dimensions of the three models for approximating OSLD cavity size and geometry.

	Model 1	Model 2	Model 3
Sphere radius	0.015 cm	0.097 cm	0.2 cm
Sphere volume	$1.41 \times 10^{-5} \text{ cm}^3$	0.0038 cm^3	0.034 cm^3
Mean chord length	0.02 cm	0.13 cm	0.27 cm

chord length of each model of approximation are provided in Table 1.

Burlin cavity theory consists of two components to account for both the dose that arises from the secondary electrons crossing the cavity and the dose from the secondary electrons that are created inside the cavity. Although many modifications of Burlin theory have been proposed, Miljanic and Ranogajec-Komor⁽⁸⁾ found that the most general expression of Burlin cavity theory is in good agreement with experimental results; therefore, the general Burlin cavity theory shown in Equation (1)^(8, 12) was used to calculate the dose to the OSLD:

$$\frac{D_{\text{cav}}}{D_{\text{med}}} = d \frac{(\bar{S}/\rho)_{\text{cav}}}{(\bar{S}/\rho)_{\text{med}}} + (1 - d) \frac{(\mu_{\text{en}}/\rho)_{\text{cav}}}{(\mu_{\text{en}}/\rho)_{\text{med}}} \quad (1)$$

In this expression, D_{med} is the dose to the medium (water), D_{cav} is the dose to the cavity (OSLD) and the ratio between these two parameters describes the response of the OSLD relative to water. Also in Equation (1), $(\bar{S}/\rho)$ and (μ_{en}/ρ) denote the ratios of the average mass stopping power and mass energy absorption coefficient (for the cavity and medium, respectively). The average mass stopping power included in this expression is the average stopping power for the spectrum of electrons generated from a monoenergetic photon. For $\text{Al}_2\text{O}_3\text{:C}$, the mass stopping power values were determined based on the weight fraction of the mass stopping powers of aluminium and oxygen. The fraction of carbon was not included in the determination of stopping power in accord with a finding of a previous work by Mobit *et al.*⁽¹⁸⁾—the energy response of pure Al_2O_3 is not different from that of 1 % carbon-doped Al_2O_3 . Data on stopping power were taken from Johns and Cunningham for each material⁽¹⁹⁾, and the mass energy absorption coefficient and range data were collected from data tables maintained by the National Institute of Standards and Technology (NIST)^(20, 21).

The parameter d in Equation (1) describes the average value of the relationship between the electron fluence generated in the cavity wall and the

initial equilibrium electron fluence, and its value depends on the size of the cavity as well as the energy of the incident photon spectra. The extreme values 1 and 0 provide the traditional formalisms for small or large cavity theory⁽¹²⁾. The parameter d was determined as a function of the incident photon energy for each dosimeter model (Table 1), using the following expression.

$$d \equiv \frac{\bar{\Phi}_w}{\Phi_w^c} = \frac{1 - e^{-\beta L}}{\beta L} \quad (2)$$

The parameter L is equal to the mean chord length, taken as four times the cavity volume divided by its surface area (Table 1). The parameter β , which describes the build-up and build-down of the electron fluence as a function of distance into the cavity, was determined using Equation (3), where t_{max} is the maximum depth of electron penetration, approximated using the continuous slowing down approximation range for the maximum electron energy in each discrete energy bin⁽¹²⁾. A value of 0.04 was recommended by Janssens *et al.*⁽²²⁾ on the basis of his model, because it was found to be most consistent with experimental data at energies similar to those in the current study.

$$e^{-\beta t_{\text{max}}} = 0.04 \quad (3)$$

The dose to the OSLD (D_{cav}) can therefore be calculated as shown in the following equation.

$$D_{\text{Al}_2\text{O}_3:\text{C}} = D_{\text{water}} \times \left[d \frac{(\bar{S}/\rho)_{\text{Al}_2\text{O}_3:\text{C}}}{(\bar{S}/\rho)_{\text{water}}} + (1 - d) \frac{(\mu_{\text{en}}/\rho)_{\text{Al}_2\text{O}_3:\text{C}}}{(\mu_{\text{en}}/\rho)_{\text{water}}} \right] \quad (4)$$

Determination of the energy response

At lower energies, $\text{Al}_2\text{O}_3:\text{C}$ will experience a greater number of photoelectric interactions than tissue, as evidenced by the differences in the mass energy absorption coefficients of the two materials. There are also differences in stopping power that will impact the relative energy response of the OSLD under conditions where secondary electron equilibrium does not exist.

The response of the OSLD (versus water) as a function of photon energy was determined as shown in Equation (5) for a comprehensive range of photon energies. Each of the components in Equation (5) is

a function of photon energy, and the energy response depends only on d and tabulated data.

$$\begin{aligned} R_{\text{Al}_2\text{O}_3:\text{C}:\text{water}}(E) &= \frac{D_{\text{Al}_2\text{O}_3:\text{C}}(E)}{D_{\text{water}}(E)} \\ &= d(E) * \frac{(\bar{S}/\rho)_{\text{Al}_2\text{O}_3:\text{C}}(E)}{(\bar{S}/\rho)_{\text{water}}(E)} \\ &\quad + (1 - d(E)) \frac{(\mu_{\text{en}}/\rho)_{\text{Al}_2\text{O}_3:\text{C}}(E)}{(\mu_{\text{en}}/\rho)_{\text{water}}(E)} \end{aligned} \quad (5)$$

Furthermore, the dependence of the energy response on the full photon energy spectrum was investigated. The response was determined for three arbitrary photon energy spectra, using the complete spectral information, as well as using only the mean photon energy. The three investigated spectra include one that is relatively soft (low energy), one medium and one relatively hard (higher energy). These three spectra were previously determined from simulations of spectra occurring in and around the primary photon beam from a Varian medical linear accelerator^(6, 23, 24). For each of the three spectra, the absorbed dose to water was estimated as collision kerma in the medium (water), using the complete spectrum, the expression for which is given in the following equation.

$$D_w = \sum_E \Psi_E \left(\frac{\mu_{\text{en}}}{\rho} \right)_{\text{water}, E} \quad (6)$$

The water collision kerma is a good approximation for the absorbed dose to water (Equation 6) when secondary electron equilibrium is present, as is the case for the specific condition used here: a water cavity contained in a water medium beyond the build-up region at the water surface.

In practice, it is necessary to identify the difference in dosimeter response for different photon spectra so that appropriate corrections can be made. Generally, standard dosimeters are irradiated using some reference energy (often ^{60}Co), but experimental measurements are made using some other photon energy. The difference in response between the experimental energy and the reference energy is defined here as the RR (Equation 7). The dosimeter response could then be corrected by multiplying the measured dose by the inverse of the RR.

$$\text{RR} = \frac{R_{\text{Al}_2\text{O}_3:\text{C}:\text{water}}|_{\text{experimental}}}{R_{\text{Al}_2\text{O}_3:\text{C}:\text{water}}|_{\text{reference}}} \quad (7)$$

Figure 1. Variation of d as a function of photon energy for three approximations of the OSLD cavity size.

RESULTS

Use of cavity theory to determine energy response

The response of aluminium oxide OSLDs was calculated using Burlin cavity theory for three cavity models (Table 1) that differed by the parameter d (Equation 2). Figure 1 shows the variation in d as a function of photon energy for the three models considered. Values of d close to unity imply a small cavity with dose deposition dominated by the electrons crossing the cavity, while values close to 0 imply a large cavity where the dose is dominated by the electrons generated from photon interactions within the cavity. The larger cavity model of the OSLD (Model 3) is associated with much smaller values of d , indicating a greater dominance of photon interactions to the dose. However, regardless of the model, at low photon energies, the deposited dose was dominated by the electrons produced in the cavity (i.e. photon interactions), and dose therefore depends on the mass energy absorption coefficient.

The energy response of the OSLD was calculated as a function of photon energy for each of the OSLD cavity models. Despite the large difference in d as a function of cavity size, there was little variation in the energy response. The response of $\text{Al}_2\text{O}_3\text{:C}$ in terms of the ratio of absorbed dose to the dosimeter versus absorbed dose to water as a function of photon energy is shown in Figure 2 for each of the three models. At the most, the three different models showed a difference in energy response of 12 %, occurring for monoenergetic photon energies near 100 keV.

While the energy dependence of the OSLD is close to unity for energies above 100 keV, the OSLD overresponds dramatically relative to water at energies below this. The response reaches a maximum in excess of a factor of 3.5 at energies around 20 keV. Model 2 (solid line) approximates the OSLD disc as

Figure 2. Relationship between dose to cavity and dose to medium calculated using Burlin cavity theory for several different sized cavities.

Figure 3. Three unique photon energy spectra with similar mean energies.

a sphere of equivalent volume and was used for all remaining calculations.

Dependence of energy response on photon spectra

The RR was determined for three photon spectra taken from Scarboro *et al.*⁽⁶⁾. These three spectra have very similar mean photon energies but vary in the distribution of photon energies (Figure 3).

The impact of the photon spectra on the OSLD response was evaluated by comparing the RR determined using the full photon spectra (Figure 3) and that determined using only the mean photon energy. The mean photon energy was calculated using photon fluence. The RR (Table 2) was the ratio between the absorbed dose to the OSLD material and the absorbed dose to water of the arbitrary spectrum relative to a pure ^{60}Co photon source ($E=1.25$ MeV). When the RR was calculated using the mean

Table 2. RR [using a ^{60}Co source ($E=1.25$ MeV) as the standard energy] for three unique spectra calculated using both mean photon energy and full spectral information.

	Soft spectrum	Medium spectrum	Hard spectrum
Mean photon energy (MeV)	0.54	0.56	0.66
$\text{RR}_{(\text{Al}_2\text{O}_3:\text{C to water})}$ (using complete spectra)	1.12	1.06	1.06
$\text{RR}_{(\text{Al}_2\text{O}_3:\text{C to water})}$ (using mean energy)	1.02	1.01	1.01

energy of the spectra, almost identical responses were found that were very close to unity. In contrast, when the spectra were considered, the RR varied, and was up to 10 % different from the RR predicted with mean energy alone. Spectral information is more important for beams with a large component of photons with energies below 100 keV, such as those found in diagnostic imaging photon beams. However, this analysis indicates that full spectral consideration may be necessary for accurate dosimetry with OSLD, even at relatively high energies.

Comparison of calculated and measured energy response

Because of the theoretical basis of the energy response calculated in this work, it is appropriate to compare the results calculated using cavity theory with measured energy response factors. The calculated energy response was compared with the measured energy response for a subset of irradiation conditions in water from a typical medical radiotherapy photon beam. Radiation field size, depth in water and distance from central axis were varied to create five unique irradiation conditions, and the photon spectra at these locations were previously simulated using a benchmarked Monte Carlo model of a Varian 6-MV linear accelerator⁽⁶⁾. The five spectra are shown in Figure 4, and are identified by radiation field size and mean photon energy. The mean energy ranged between 1.46 and 0.19 MeV.

The energy response for each of these spectra was determined using Burlin cavity theory, and then the energy response under identical conditions was measured. All measurements were carried out using a Varian Clinac 21EX accelerator (Varian Medical Systems, Palo Alto, CA, USA) with a 6-MV photon beam, calibrated using standard industry protocols⁽²⁵⁾. The measured RR is defined as the ratio of the dosimeter signal per delivered dose of the experimental condition to the standard condition

Figure 4. Monte Carlo simulated photon spectra for five measurement positions using a Varian 6MV photon beam.

(signal per delivered dose using a ^{60}Co beamline), as defined in the following equation.

$$\text{RR}_{\text{measured}} = \frac{(\text{signal/dose})_{6\text{ MV}}}{(\text{signal/dose})_{^{60}\text{Co}}} \quad (8)$$

The calculated and measured RRs differed by <1.7 % (root-mean-square error) for the range of energies examined (Table 3).

Comparison with energy response reported in the literature

The results calculated using cavity theory were also compared with the measured energy response factors that appear in recent literature. The energy response has been evaluated for a range of specific photon beams, in particular kilovoltage beams including mammography, computed tomography and general radiography^(13–15, 18, 26). Because of the need for spectral data to complete the analysis, this investigation focused on a comparison with measured energy response for kilovoltage beams by Reft⁽¹⁵⁾. Spectra were generated using the SpekCalc program⁽²⁷⁾ to match the beam quality (using peak photon energy and first half-value layer) of the corresponding spectra used by Reft. Calculated energy responses were made with cavity theory using these spectra and the values were compared with those reported by Reft (Table 4). The results showed good agreement, with average absolute differences within 6 %.

DISCUSSION

The response of $\text{Al}_2\text{O}_3:\text{C}$ OSLDs is dependent on radiation energy and is dominated by differences in photon interactions, most notably photoelectric interactions, between the dosimeter and the

Table 3. Comparison of energy responses relative to ^{60}Co ($E=1.25$ MeV) for selected measurement positions in a 6-MV therapy beam.

Field size (cm $\times$ cm)	Depth in water (cm)	Distance off central axis (cm)	Mean photon energy (MeV)	Calculated response	Measured response	Difference (%)
10 $\times$ 10	20	0	1.46	1.020	1.028	0.8
20 $\times$ 20	5	5	1.15	1.025	1.024	0.0
5 $\times$ 5	5	20	0.66	1.100	1.095	-0.4
10 $\times$ 10	20	15	0.31	1.196	1.171	-2.1
20 $\times$ 20	20	30	0.19	1.408	1.381	-2.0

Measured values were measured using a Varian 21EX accelerator, and calculated values were determined using spectra generated using a benchmarked Monte Carlo model of a Varian 6-MV accelerator.

Table 4. Comparison of calculated energy responses relative to ^{60}Co ($E=1.25$ MeV) determined using cavity theory for OSLD with measured values reported in the literature for photon beams of varying energies.

Beam specifier (kVp)	Mean photon energy ^a (keV)	Half-value layer ^a	Calculated response	Literature-reported response ^b	Percent difference (%)
125	53.3	3.4 mm Al	3.27	3.40	-3.7
150	67.2	0.42 mm Cu	2.59	2.92	-11.2
200	81.3	0.82 mm Cu	2.10	2.11	-0.6
250	109	1.92 mm Cu	1.52	1.64	-7.3

^aSpekCalc⁽²⁷⁾.

^bReft⁽¹⁵⁾.

medium. Burlin cavity theory was used to theoretically determine the response of Al_2O_3 as a function of photon energy. At low energies ($E < 100$ keV), the dosimeter can overrespond by a factor of 3.5 or more relative to ^{60}Co . This would mean that unless accounted for, the dosimeter reading would report a dose 3.5 times higher than the actual dose to water at that location. For higher photon energies ($E > 1$ MeV), the dosimeter has a response close to that of water. This is consistent with the findings in the literature that report a difference in the energy response between 6 MV photon beams and ^{60}Co of 1–4.5 %^(15, 18), and < 2 % between 6 and 18-MV photons^(2, 15, 18). However, measurement using OSLD in photon beams that include a considerable low-energy component will be affected by this exaggerated response and may need to be corrected.

The energy response was calculated for a sample of polyenergetic beams and compared with measured values (Table 3) as well as values reported in the literature (Table 4). For the Monte-Carlo-simulated spectra examined, the authors' Burlin-cavity-calculated energy responses showed good agreement with the measured energy responses (1.7 % root-mean-square error). A comparison with energy response values reported in the literature⁽¹⁵⁾ had more varied agreement. The difference between the cavity theory response and the measured energy response in the

literature varied from < 1 to 11 %, with an average difference of 5.7 %. While spectra were matched using half-value layer, mean energy and filtration, there likely remain differences between the spectra used to complete the measurements and those generated using SpekCalc. This deviation is attributed differences between the SpekCalc and the actual spectra. This difference also suggests that when RR is calculated with Burlin cavity theory, as conducted here, a major source of uncertainty is the detailed knowledge of the underlying spectrum. If the spectrum is very well known, better than a 2 % agreement is achievable (Table 3). However, uncertainty in the spectrum can readily reduce the agreement to ~ 10 % (Table 4).

The calculated energy response based on mean spectral energy differs from the calculated energy response determined using an integration over the entire spectrum, which becomes important for polyenergetic beams. For example, for the three photon spectra shown in Figure 3, the relative energy response was 1.01–1.02 when based on mean energy, but was 1.06–1.12 when the entire spectrum was considered. This difference arises because using the mean photon energy may cause the overresponse of the low-energy component of the spectrum to be underestimated. For the spectra presented here, if the dose was corrected using a

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Figure 5. Aluminum oxide energy response, when compared based on mean energy and not the complete spectrum, shows substantial errors (up to 50%) in the estimated relative response.

factor determined using only the mean energy, the reported measured dose could be erroneous by up to 10 %.

To illustrate further the importance of considering the complete photon energy spectrum, the reported energy response for various photon beams has been plotted against the authors' Burlin cavity determined energy response (Figure 5). Although the line shows general agreement with the points, there are differences of up to 50 %. These large differences are the result of the points being plotted at their mean energy and thereby under accounting for the over-response at low energy. When the full spectrum is considered, the cavity theory accurately predicts such RRs (as shown in Table 3).

The uncertainty in the cavity-theory-calculated response includes the uncertainty in the photon energy spectra (dominated by the systematic uncertainty in acquiring accurate spectral information for kilovoltage spectra), statistical uncertainty from Monte Carlo simulations and the uncertainty in the tabulated data for the mass energy absorption coefficients and stopping powers. Spectral information below 10 keV was not considered on account of the increased uncertainty in tabulated stopping power data at low energies. The estimated uncertainty in the stopping power is typically on the order of 2–3 % for low-Z materials down to 10 keV, but on the order of 10 % for 1 keV⁽²¹⁾. The comparison with the measured energy response supports the accuracy of the authors' application of cavity theory to $\text{Al}_2\text{O}_3\text{:C}$ dosimeters for a variety of photon spectra found in a medical setting, including modalities appearing in radiation therapy and diagnostic imaging. Cavity theory calculations are a viable alternative or supplement to measurements or Monte Carlo simulations; however, this analysis has highlighted the importance of accurate spectral information.

Figure 6. Energy response of two common dosimeters: LiF TLD and $\text{Al}_2\text{O}_3\text{:C}$ OSLD, calculated using Burlin cavity theory.

Figure 7. The ratio ($\text{Al}_2\text{O}_3\text{:water}$) of mean electron collisional stopping power and mass energy absorption coefficient as a function of photon energy.

Owing to several substantial advantages, OSLDs are often used instead of TLDs. However, because the mass energy absorption coefficients of Al_2O_3 are greater than those of LiF⁽²⁰⁾, it would be expected that OSLDs would have a disadvantage in the form of a larger energy response. That is, the discrepancy between the dosimeter and water would be magnified for Al_2O_3 compared with LiF. In Figure 6, the RR of LiF TLDs is shown⁽⁶⁾ with the RR of Al_2O_3 OSLDs, both calculated using Burlin cavity theory.

For low photon energies, LiF may overrespond by ~50 % relative to water; for the same energies, Al_2O_3 may overrespond by a factor of 3.5 or more. For higher energies, the response of the dosimeter relative to water is very similar (within a few percent); however, the low-energy scatter component of a photon beam with a high mean energy could substantially impact on the response of Al_2O_3 .

The sensitivity of Burlin-cavity-predicted energy response values were only minimally affected by the size of the cavity—the different models had very different values for the parameter d , but the energy response for a monoenergetic photon beam varied by <12 %, because d decreases with decreasing energy and is <0.2 for photon energies <100 keV for each of the three models, which is the energy where the divergence of the mean collisional stopping power and mass energy absorption coefficients begins to occur (Figure 7). At higher energies, the models are different (different values of d), but the ratios of coefficients are the same, so no differences manifest in the energy response. At low energies, the relative coefficients are different, but the models all approach $d=0$, so again, no differences manifest in the energy response.

While Burlin cavity theory offers sufficient estimation of the energy response, there are several limitations to this approach. The authors' calculations considered only the dosimeter material and did not include an approximation of the plastic cassette surrounding the dosimeter and the associated dosimetric coefficients. This cassette is very small (<1 mm thickness) and is made from a tissue-equivalent plastic. Because simulations were carried out in water and full scatter conditions, the presence of a water-equivalent cassette will not alter the dosimeter response. The calculation of energy response using cavity theory also does not consider any angular dependence, which has been shown to have an increasing effect as energy decreases^(26, 28).

CONCLUSIONS

$\text{Al}_2\text{O}_3\text{:C}$ is a common material for use in OSLD, and the use of these dosimeters is becoming increasingly prevalent in medical environments. This material has a known energy dependence, and in this work the energy dependence was determined using general Burlin cavity theory. The approach described here is suitable for determining the energy response of OSLD to any arbitrary spectra without the need for measurement or Monte Carlo calculations, which has not been previously reported in the literature. This approach was found, through a comparison with the responses reported in the literature, to be accurate within 2 % on average when reliable spectral data are available. The results of this work have therefore indicated that cavity theory can be used to predict the energy response of OSLD with comparable accuracy to high-precision measurements or Monte Carlo simulations.

For low-energy photons ($E < 100$ keV), OSLDs have a substantial overresponse—as much as a 3.5-fold effect for some energies. If not accounted for, this overresponse could introduce substantial inaccuracies into dose measurement using OSLDs. If calculated with

cavity theory, it is necessary to determine such a correction factor using the entire photon energy spectrum rather than the mean photon energy.

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