Energy dependence (75 kVp to 18 MV) of radiochromic films assessed using a real-time optical dosimeter

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The response of radiochromic film, GafChromic™ EBT, was investigated for dependence on x-ray beam energy using a previously reported real-time optical readout approach. X-ray beams of energy from 75 kVp to 18 MV were employed. The dose-induced change in optical density for the EBT film was compared to values obtained for GafChromic™ HS and MD-55 films, exposed under the same conditions. All responses were normalized to that obtained for ^{60}Co irradiation. While change in optical density for 1 Gy of applied dose as measured with HS and MD-55 films decreased by approximately 40% at low energies, the mean change in optical density of EBT film remained within 3% of that in the ^{60}Co beam over the entire energy range. © *2007 American Association of Physicists in Medicine*. [DOI: 10.1118/1.2431425]

Key words: energy dependence, radiochromic film, densitometry, dosimetry

I. INTRODUCTION

Measurements of ionizing radiation dose are often required in diagnostic radiology, radiation therapy, health physics, and other scenarios. It is thus of interest to find a robust dosimeter that can be used across a wide range of radiation types and for various purposes, in order to decrease the complexity of radiation dosimetry and to permit assurance of appropriate radiation levels without excessive effort or cost. Such a dosimeter would have to meet several criteria,[1] including small size for *in situ* use, real-time response, and independence of measured signal across all x-ray energies of interest. Ideally, the detected dose from such a dosimeter should be equivalent to that delivered to water or tissue, so called "energy-independent response". This will enable the dosimeter calibration at any beam energy for which the operator has confidence in the absolute dosimetry (e.g., ^{60}Co), and then its use with any beams without energy-dependence correction.

Recently, two radiochromic films (GafChromic™ MD-55 and EBT) made by International Specialty Products (ISP, Wayne, NJ) have been considered as potential candidates for *in situ* real-time optical dosimetry.[1,2] Although GafChromic™ MD-55 (equivalent to MD-55-2 referred to in some publications,[3] and henceforth referred to as MD-55) performed reasonably with respect to ideal real-time dosimeter criteria,[1] it has been shown by traditional measurements (waiting some time after irradiation) of optical density to decrease in response as energy decreases.[4] The response of GafChromic™ HS (hereafter referred to as HS) relative to that of MD-55 for traditional measurements was recently summarized[5] and appears to be similar across the energy range tested. Investigations of other versions of radiochromic films with the same sensitive material as currently used in MD-55 and HS showed the same trend.[6–8] On the other hand, GafChromic™ EBT (henceforth referred to as EBT) was suggested by its manufacturer to have a response to dose-to-water that is independent of energy since it has an effective atomic number (Z_{eff} of 6.98 as quoted by the manufacturer) closer to that of water (Z_{eff}=7.3) than Z_{eff} of 6.5 for MD-55. However, Z_{eff} is just a first order approximation to how these complex films interact with photons at various energies. It gives no hint to whether all photon energies are equally effective at inducing polymerization within the sensitive medium. For this reason, it is important to investigate whether optical density of radiochromic films changes with photon beam energy. Several authors have recently reported on energy dependence of EBT.[9,10] One report used a very large range of dose rates for the different irradiations,[9] thus possibly introducing extraneous errors to the optical density measurements. The other reports optical density measurements taken 24 h after irradiation,[11] making the data inappropriate for evaluation of energy independence of EBT in real-time dosimetry.

Since the radiochromic media are being investigated for real-time dosimetry purposes, trends in the films' response observed after some time has elapsed since irradiation need to be verified in real-time as well. In this paper, we compare the change in optical density as measured immediately at the end of irradiation for 1 Gy delivered to previously unexposed MD-55, HS, and EBT films for a number of beams of a range of photon energies (75 kVp to 18 MV).

II. METHODS AND MATERIALS

A. Solid Water™ phantom

A $30\times30\times4$ cm^3 water equivalent phantom (Solid Water™) was made for the experiments (Fig. 1). Two sets of inserts were designed: one for ion chamber measurements, the other for the radiochromic film measurements, where the latter is shown on the right of Fig. 1. The former was made such that the center of the ion chamber (Model 2571, NE Technology Ltd., UK; calibration traceable to National Research Council) measuring volume was located in the middle

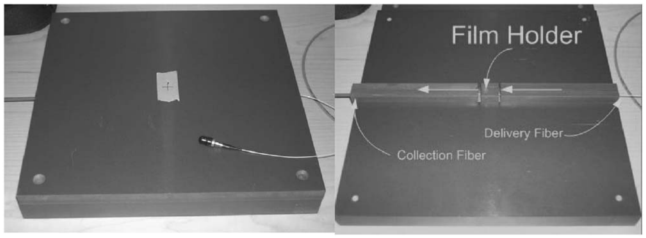

FIG. 1. 30 cm × 30 cm × 4 cm phantom with the film insert (assembled left, and without the top half on the right). The center of film positioned within the film holder is located in the middle of the 30 cm × 30 cm plane. Delivery and collection optical fibers are positioned at 1.5 cm depth within the phantom, such that the interrogation light path is perpendicular to the film plane (as shown by straight white arrows).

of the 30×30 cm^2 plane at a depth of 1.5 cm. The latter was designed such that the center of the 1×1 cm^2 piece of film (MD-55 from Lot L1906 MD55, HS from Lot L0445HS, and EBT from Lot 35322-003I) is positioned at the center of the 30×30 cm^2 plane at a depth of 1.5 cm, with the plane of the film perpendicular to the largest surface of the phantom. The dimensions of optical fiber-based read-out chamber were described previously.[1] Briefly, a 50/125 μm (core/cladding diameter) delivery optical fiber and the 1.50/1.55 mm collection fiber are located co-axially through the optical assembly. The fibers are 5.0 mm apart and are configured such that the measurement aperture at the plane of the film is ~650 μm in diameter. The details of optical measurements are discussed below.

B. Ionizing radiation exposures

For all irradiations, slabs of Solid Water™ were added to the bottom (and top, depending on the beam energy) of the phantom to create a total thickness of 10 cm. The six photon beams used for ionizing radiation dose measurements are summarized in Table I.

For the low-energy range, an orthovoltage treatment unit (Pantak Therapax DXT 300), calibrated using an in-house protocol with TG 21 methods, was used. The 1×1 cm^2 pieces of film were irradiated to 1 Gy at 2.0 cm depth, 100 cm SSD, with 10×10 cm^2 field at SSD as per TG 61 specification,[13] with no correction for use of Solid Water™ instead of water, given their similarity at orthovoltage energies.[14,15] While 100 cm SSD for orthovoltage treatments is not used clinically, the setup described in TG 61 and used here allowed for easy verification of dose at the depth at which film measurements were performed. The nominal dose rates were 8, 14, and 15 cGy/min for 75, 100, and 225 kVp beams, respectively. The stability of machine output was verified using the same setup and TG 61 with the ion chamber before and after film measurements, for all orthovoltage beams. The two measurements always remained within 3%, and 90% of the time within 1% of each other. The ratio of the mean mass energy-absorption coefficients of water to air ($[(\mu_{en}/\rho)^{w}_{air}]_{water}$), and the overall chamber correction factor ($P_{Q,cham}$) were extrapolated down to the energy of the75 kVp beam from the data listed in the protocol.

For ^{60}Co measurements, a Hemitron, designed and made at the Ontario Cancer Institute for total body irradiation, was used. An electron and beam flattening filter #2 was selected.[12] The films were irradiated to 1 Gy at 1.5 cm depth, 90 cm SSD, with a 10×10 cm^2 field defined at 90.5 cm at an approximate dose rate of 33 cGy/min. The output of the ^{60}Co machine was first calculated knowing the activity measured during annual calibration, the decay constant, and the

TABLE I. The x-ray beams employed in these investigations (Therapax DXT 300, Hemitron (Ref. 12) and Elekta Synergy).

Machine	X-ray beam	Nominal energy (keV)	Description (beam parameters, filtration if any, machine calibration protocol)
Therapax DTX 300	75 kVp	34	30 mm A1 HVL, 30 mA tube current, 1.65 mm A1 inherent filtration, TG21 protocol
Therapax DXT 300	100 kVp	39	4.5 mm A1 HVL, 30 mA tube current, 2.4 mm A1 inherent filtration, TG21 protocol
Therapax DXT 300	225 kVp	116	1.8 mm Cu HVL, 13.4 mA tube current, 0.9 mm Cu +1 mm A1 inherent filtration, TG21 protocol
Hemitron[a]	^{60}Co	1250	1170 and 1330 keV photons, flattening filter #2,[a] PDD(10)=0.587, TG21 protocol
Synergy	6 MV	2700	$TPR20/TPR_{10}=0.687$, PDD(10)=0.678 with TG51 protocol
Synergy	18 MV	5650	$TPR20/TPR_{10}=0.775$, PDD(10)=0.784 with TG51 protocol

[a]Reference 12.

elapsed time in days since that measurement; the setup was then verified by measuring the dose to water at 1.5 cm depth with the ion chamber.

For 6 MV measurements, the films were irradiated at 1.5 cm depth, at 100 cm SAD, with the $10\times10\ \mathrm{cm}^2$ field defined at SAD. The average dose rate was 13 cGy/min, achieved using a low dose rate mode of the accelerator. For 18 MV measurements, a 3.0 cm depth, 100 cm SAD, and a $10\times10\ \mathrm{cm}^2$ field defined at SAD were used. The average dose rate used was 21 cGy/min. Since the effect of dose-rate variations on real-time ΔOD measurements of EBT have not been investigated in depth yet, low dose rates in megavoltage beams were used to try to eliminate any extraneous errors, so that the variation in ΔOD could be attributed mostly to variation in energies of the beams, and less so to other factors.

For both 6 and 18 MV, an Elekta Synergy® linear accelerator was used. The linear accelerator was calibrated using TG 51 protocol to produce 1 cGy per monitor unit at $d_{\max}$, 100 cm SAD, for a $10\times10\ \mathrm{cm}^2$ field at SAD. After machine calibration, output is measured using a 7×7 matrix of ion chambers[16] and, prior to irradiations of films, stability of machine output was verified using the same equipment. Minor deviations in output ($1\pm2\%$ cGy per monitor unit) were corrected for to produce the closest value to the desired 1 Gy dose.

C. Optical measurements

A broadband light emitting diode (Luxeon III Star from Lumileds, San Jose, CA) fiber-coupled (Doric Lenses Inc., Ancienne Lorette, Quebec, Canada) to a 600 μm core fiber was used as the light source. The emitted light passes through a 500 nm high-pass filter (FEL500, Thorlabs Inc., Newton, NJ) before being coupled into a 600 μm core, 17 m long optical fiber connected to the delivery fiber in the phantom. The optical power delivered to the film was not measured, but was found to be low enough to not affect the measured ΔOD. The light exiting this fiber passes through the GafChromic™ film and is incident on a collection fiber that is coupled to the Ocean Optics spectrophotometer.[1] The spectra were always collected at ~1 Hz, by adjusting the number of spectra averaged and the integration time on the spectrophotometer prior to irradiation in order to obtain maximum signal without saturation. The acquisition of spectra began approximately 10–15 s prior to the start of the ionizing radiation emission, and continued for another 20 s to 3 minutes after the end of irradiation, depending on the experiment. The change in optical density (ΔOD) for a given 1 Gy irradiation was calculated by first plotting OD (630–640 nm for EBT film, and 670–680 nm for MD-55 and HS) versus time, and then subtracting OD measured immediately before irradiation from that measured immediately after,[1,2] yielding ΔOD per 1 Gy of dose applied.

III. RESULTS & DISCUSSION

Figure 2 shows the ΔOD as a function of time for MD-55, HS, and EBT irradiations to 1 Gy at the average rate of 8 cGy/min. The figures illustrate that the real-time response

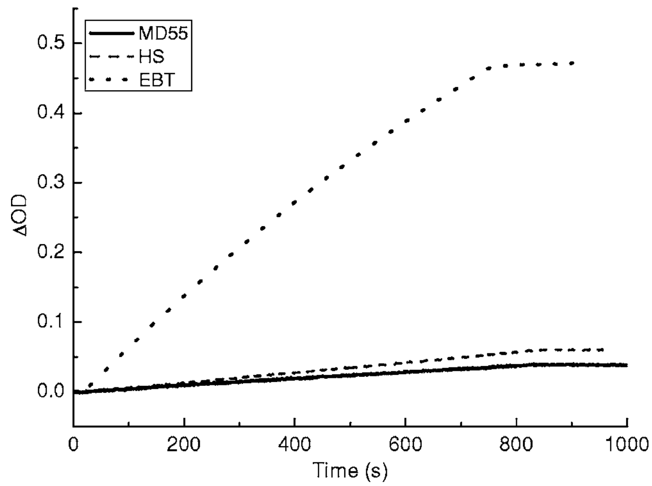

FIG. 2. Sample of time-dependent change in OD with time for a 1 Gy irradiation with a 75 kVp Therapax DXT 300 beam at 8 cGy/min for MD-55, HS, and EBT film. The delay at the beginning illustrates no increase in OD while the beam is off, then the increase in ΔOD is observed during irradiation, and another flat line after the beam is turned off.

is present for all three films even at very low dose rates (8 cGy/min). The slope of ΔOD increase during irradiation is steeper for EBT than that for HS or MD-55. A higher real-time EBT response, compared to MD-55, was also previously seen for the 6 MV beam.[2] Also, just like for irradiations at other x-ray energies, EBT's response is nonlinear with dose[2,9,17] and its postexposure development exists. However, neither the non-linearity of response with dose nor rates of postexposure development were investigated explicitly in this paper.

The change in optical density for 1 Gy total dose for MD-55, HS, and EBT films at each of the energies used are shown in Fig. 3, plotted with 2σ error bars since 1σ are too small to visualize. In Figs. 4(a)–4(c), the same data are nor-

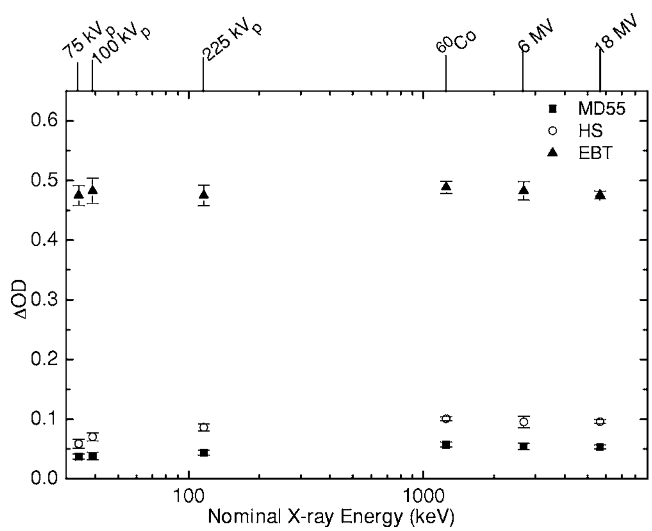

FIG. 3. Un-normalized ΔOD for 1 Gy total dose for MD-55, HS, and EBT films for irradiations delivered at various equivalent x-ray energies, presented to illustrate variations in sensitivity of the three films considered in this study (error bars represent two standard deviations, 2σ).

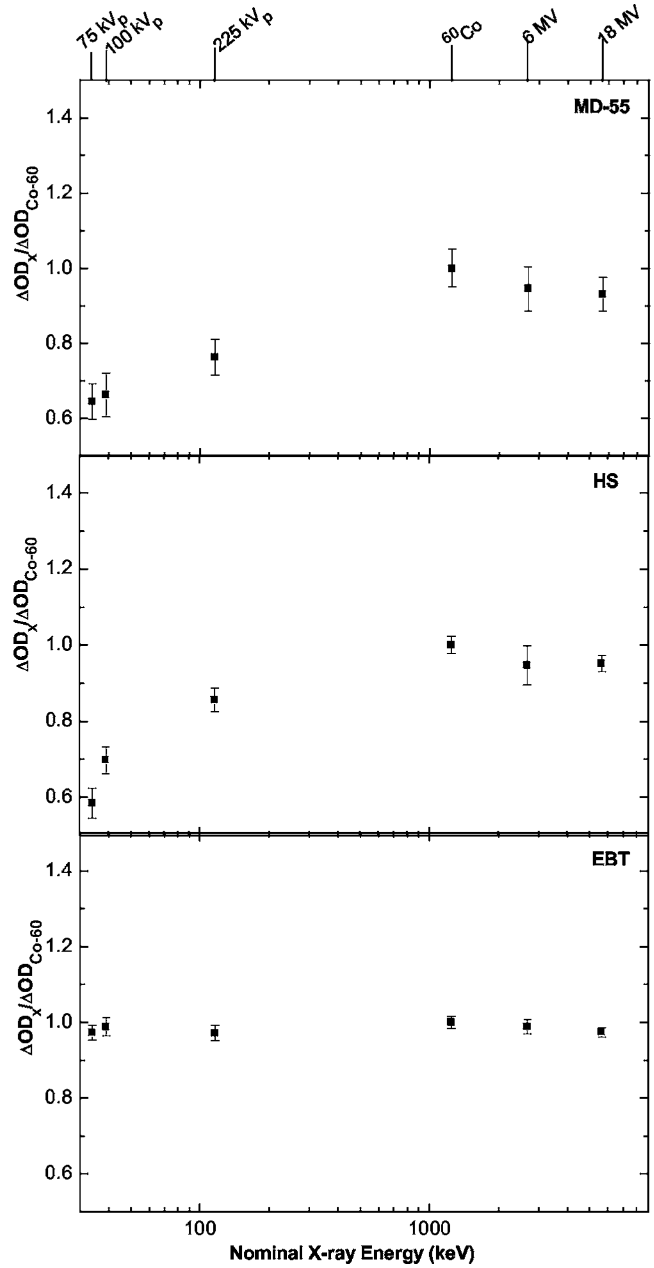

FIG. 4. ΔOD/Gy for MD-55, HS, and EBT, as a function of equivalent x-ray energy. Results are normalized to ΔOD/Gy delivered with the ^{60}Co source (error bars represent 1σ).

malized to the ^{60}Co value. The percent standard deviations in these plots (ranging 4.5%–5.9% for MD-55, 2.2%–5.1% for HS, and 1.2%–2.8% for EBT) are expected given the previously reported (ISP product information) nonuniformity of response within a single sheet of these films (quoted to be 4%, 3%, and 1.5% one standard deviation for MD-55, HS, and EBT, respectively). This nonuniformity component of individual film response was investigated using the same film for multiple serial exposures, by first delivering 1 Gy with ^{60}Co, and then normalizing subsequent irradiations applied at the other energies. For the MD-55 film (at orthovoltage exposures), we found the percent standard deviation of the normalized data dropped from 4.5%–5.9% to 0.8%–3.1%. However, for this technique to work with EBT, some form of nonlinearity correction may have to be applied, given its nonlinear response with dose as seen in Fig. 3 and as previously reported.[2,9,17] In addition to the decrease in variance, the "preexposure" altered the apparent sensitivity of the MD-55 response for orthovoltage irradiations, which was observed to increase considerably (by 8.5% on average). This increase is attributed to postexposure development from the initial calibration dose, which leads to a significant overestimate of ΔOD for all subsequent doses because of long irradiation times at this machine's low dose rate levels. Because of the stated issues with this technique, preexposure on ^{60}Co for each film was not used.

TABLE II. Comparison of response of EBT film, normalized to response at 6 MV, as measured approximately 24 h after exposure to that measured immediately at the end of exposure (error is 1σ).

X-ray beam	Response after 24 h[11] relative units (Ref. 10)	Real-time response, relative units (current study)
75 kVp	0.926±0.037	0.984±0.023
100 kVp	0.930±0.037	1.000±0.027
6 MV	1.000±0.037	1.000±0.023
18 MV	0.996±0.037	0.986±0.017

As seen in Fig. 4(a), the response of MD-55 decreases with decreasing equivalent energy by almost 40%. This is in agreement with previously published data.[4,5,18] On the other hand, delivering the dose with a 6 MV or an 18 MV beam, instead of a ^{60}Co beam, does not appear to introduce a significant decrease in response (within 5%), as previously reported.[19] The decrease in sensitivity with decreasing equivalent energy for HS film [Fig. 4(b)] is also consistent with previous results.[5,20] For EBT film, however, there appears to be no decrease in ΔOD for 1 Gy dose (referred to as ΔOD/Gy henceforth) as the equivalent energy is decreased. Every ΔOD/Gy value obtained in this study for EBT film was within 5.5% of the average ΔOD/Gy obtained at ^{60}Co, and approximately 61% of values were within 3%. Chiu-Tsao *et al.* have published some results on dependence of EBT response on radiation energy, using Pd-103, I-125, Ir-192, and 6 MV x-ray beam.[9] They have also reported minimal photon energy dependence of response (within 10% error).

Recently, Butson *et al.* also reported on the subject of EBT energy dependence,[10] but have obtained slightly different results than presented in this paper. For comparison purposes, part of that data and the data collected in this study (renormalized to the 6 MV response)[10] are illustrated in Table II. While the normalized response for 18 MV irradiation is within experimental uncertainty, it is apparent that the rest of the measurements reported here are significantly higher, which may in part be attributed to the difference between real-time measurements and those obtained approximately 24 h (Ref. 11) after irradiation.

For example, because the orthovoltage exposures are performed at low dose rate, delivering 1 Gy to a film positioned

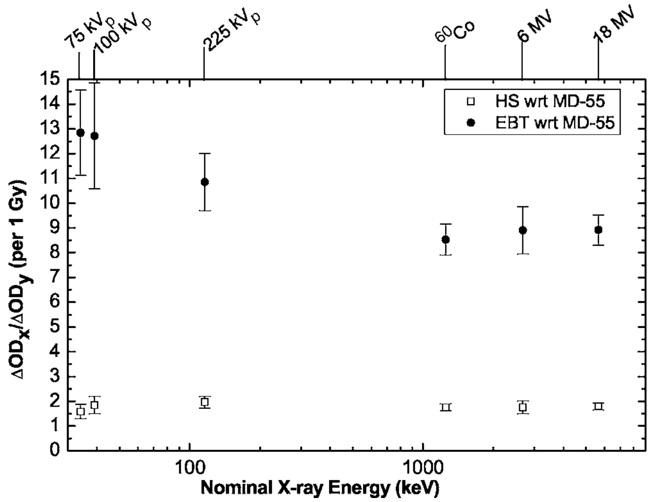

FIG. 5. Increased sensitivity of HS and EBT films with respect to MD-55, for a dose of 1 Gy (error bars are 2σ).

2 cm below the surface with a 75 kVp beam required ~13 min of beam time. Meanwhile, delivering 1 Gy with a 6 MV beam took approximately 7.5 min. Hence, the films exposed with orthovoltage beams had more time to darken before the completion of irradiation, and their real-time response compared to that at 6 MV is overestimated. However, given that the sensitive layer of the EBT film has potential for real-time dosimetry and most orthovoltage sources operate at low dose rates, this overestimate is important in characterizing this film's response. Accurately predicting by how much the EBT films would overrespond would be difficult, since the postexposure development of the partial dose delivered at the beginning of irradiation is likely a function of both total dose delivered and the dose rate of delivery, in the same manner as was shown for one of the predecessor radiochromic films.[21]

Another possible reason for the discrepancy is the choice of wavelength range used for ΔOD measurement. While our data analysis looked only at the primary absorption peak, the data analysis presented in the work by Butson *et al.* used 500–700 nm range, which includes both absorption peaks for EBT film. It is unclear how the secondary absorption peak affects the measured ΔOD, and this remains to be investigated further.

Figure 5 illustrates the response of HS and EBT films arbitrarily compared to MD-55, for the first 1 Gy delivered. The large errors are due to the high percent standard deviation for MD-55 measurements performed at low x-ray beam energies. The sensitivity of HS is approximately two times greater than that of MD-55 across the entire energy range, as previously reported for a smaller energy range by Chiu-Tsao *et al.*[22] HS and MD-55 films have the same radiosensitive material, but have a different layer structure. The fact that their ratio of sensitivities is nearly constant across a wide range of energies suggests that the response of these films is more dependent on the sensitive material used, and less so on the structure of the layers in the film. In contrast, EBT does not significantly decrease in response (ΔOD/Gy) as the energy of x-ray beam decreases. Hence at low energies (keV), response of EBT is greater in comparison to MD-55 than at high (MeV) energies.

IV. CONCLUSION

The results have shown that while ΔOD for 1 Gy total dose for HS and MD-55 drops by almost 40% when the equivalent x-ray beam energy decreases from that of ^{60}Co to 34 keV, mean normalized real-time response of EBT stays stable within 3%. The resulting response of EBT is more than ten times greater than that of MD-55 at orthovoltage energies, but only eight to nine times greater at megavoltage energies. Hence, EBT film is more suitable than either HS or MD-55 for low-energy real-time dosimetry, and across the entire energy range investigated in this paper.

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