THREE-DIMENSIONAL HIGH DOSE RATE DOSIMETRY OF PULSED ELECTRON BEAMS: THE COMBINED RADIOCHROMIC FILM AND CALORIMETRIC MEASUREMENTS

by

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Received on June 26, 2004; accepted on November 11, 2004

We present an evaluation of the precision and accuracy of image-based radiochromic film dosimetry. A stack of radiochromic film FWT-60 was used to map a radiation field produced by an electron pulse from a Febetron 707 accelerator (dose rate around 5 10^{11} Gy/s; maximum dose around 160 kGy). The three-dimensional dose distribution was obtained by a He-Ne scanning-laser microdensitometer and using image segmentation and correction for non-linear response of films. Calorimetry and electron paramagnetic resonance dosimetry were used to verify the results obtained with a FWT-60 film.

Key words: dosimetry, electrons, radiochromic films, calorimetry

INTRODUCTION

There is an increasing need for measurements of depth-dose distribution both along the beam as well as laterally, *i. e*., two-dimensional (2D) and three-dimensional (3D) dose distribution, in areas such as radiation processing, radiotherapy, radiobiology, *etc*. One possible option is stacking of radiochromic films (RCF), an approach, particularly suitable for calibration using calorimetry, that was initially proposed by Radak [1] and later employed by others [2, 3]. However, the problem of the lateral dose distribution, apart from film stacking, requires the use of 2D spatially resolved measurements of the absorbance of each film, *i. e*., the use of scanning densitometry (see *e. g*. [4]). However, an additional problem arises when a high dose and/or high dose rates are used where nonlinear dosimeter response frequently occurs. An accurate dosimetry of extremely high dose rates is rather complicated task since the dose range limits of each particular dosimeter should be determined.

In this work we examined the suitability of a FWT-60* radiochromic film in determining the 3D dose distribution from a pulsed electron beam (EB) source using scanning densitometry in assessing the dose distribution. We used an aluminum calorimeter (as a dose rate insensitive standard) in assessing the response of these RCF. The approach is somewhat similar to the one reported in the paper by Janovsky and Miller [2], however, here a high-intensity pulsed electron beam was used and dosimeter films exhibit a nonlinear response. In addition, electron paramagnetic resonance (EPR) dosimetry was used to verify the results obtained by RCF dosimetry.

EXPERIMENTAL

FWT-60 radiochromic films were purchased from Far West Technology Inc. (Goleta, CA, USA). Alanine dosimeters (0.3 mm thick plates) were prepared as previously described [5]. Fricke solution, FWT films and alanine EPR dosimeters were separately irradiated in a ^{60}Co radiation field (3 samples for each dose value, maximum dose rate around 1 Gy/s) by placing them into polystyrene phantoms with 5 mm thick walls to achieve electron equilibrium.

Scientific paper
UDC: 539.124:621.384.6:614.876
BIBLID: 1451-3994, *19* (2004), 2, pp. 24-29

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* Although commercial name of product is given, no endorsement or evaluation of merit is intended.

Electron irradiation was performed on a Febetron 707 accelerator (Field Emission Corporation) using 20 ns electron pulse of nominal energy of 2 MeV. Maximum estimated dose rate of EB is around 5 10^{11} Gy/s [6].

To obtain the dose *vs*. penetration depth relationship for electrons, a stack of 13 films (5 5 cm, thickness 0.047 0.002 mm) separated by aluminum plates (5 5 cm, thickness 0.07-0.21 mm) was placed perpendicular to the electron beam at the distance of one millimeter from the accelerator tube. The overall thickness of the stack was sufficient for total absorption of the pulsed EB. Aluminum was used as a material for spacers (instead of *e. g.* plastic) to allow direct comparison with calorimetric measurements. In the second type of experiment, alanine dosimeters (two 5 10 mm plates positioned side-by-side) were added between films (10 10 mm) and aluminum plates. EPR spectra were measured using a Varian EPR spectrometer, model E 104A, operating at X band frequency (9.5 GHz).

Calorimetry was performed with a simplified version of the quasi-adiabatic aluminum calorimeter [7]. It consists of two aluminum discs (diameter 6 cm, thickness 4 mm) connected to a copper-constantan thermocouple (sensitivity 40 V/°C). One disc, placed perpendicular to the electron beam at the distance of one millimeter from the accelerator tube, was irradiated, while the other was at room temperature. Since the diameter of the accelerator tube is only 3.3 cm, it can be safely assumed that all electrons were absorbed within the calorimeter.

To account for the possible differences of the output of the accelerator in separate irradiations of film stack and calorimeter, a RC film having same dimensions as in stacked-films experiment was placed over the side of calorimeter facing the accelerator tube. This film was analyzed in the same manner as films from stacked-films experiment and it was found that the differences in the output were negligible.

The absorbance of gamma-irradiated films was measured on a Perkin-Elmer Lambda 5 spectrophotometer at the wavelength of 633 nm. The peak absorbance of the blue colored product of irradiated films is at 605 nm [8], but we used the absorbance at 633 nm to match the wavelength of the He-Ne laser microdensitometer. In addition, such choice of wavelength enabled us to diminish the saturation effects and to make a spectrophotometric analysis to cover the high dose range employed in this work (see *e. g.* [8]). The absorbance of EB irradiated films was measured on a Pharmacia LKB Ultrascan XL microdensitometer. The light source in the microdensitometer was a He-Ne laser (wavelength 633 nm) and the film surface was scanned with a beam spot diameter of 100 m, which is more than sufficient to enable a good 2D spatial resolution.

RESULTS AND DISCUSSION

Figure 1 shows the results obtained for FWT-60 films in the ^{60}Co radiation field. The response of films used is in agreement with previous results for this type of film [9]. Subsequent measurements of absorbance of these films using microdensitometry (the entire surface was scanned) showed an excellent agreement of these two techniques in assessing absorbance, *i. e.*, the difference in measured absorbance was within the standard error of absorbance for any individual technique (<5%). This is not surprising since these films were uniformly irradiated and absorbance was measured at the same wavelength [10], however, this step was necessary since results in fig. 1 were further used

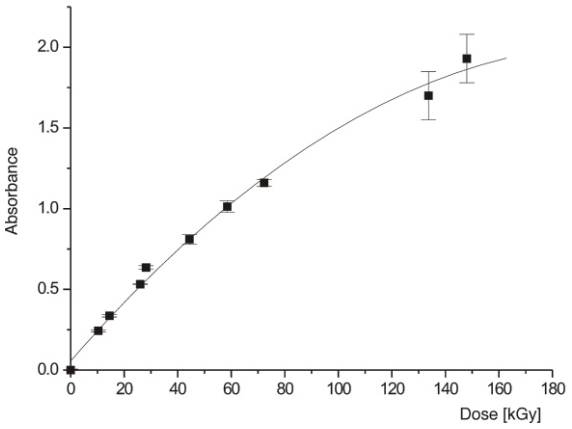

Figure 1. Dose response of radiochromic FWT-60 films irradiated with ^{60}Co -rays. Absorbance of films was measured at 633 nm using spectrophotometry, while the dose was determined by Fricke-standard. The line is obtained using a polynomial second order function

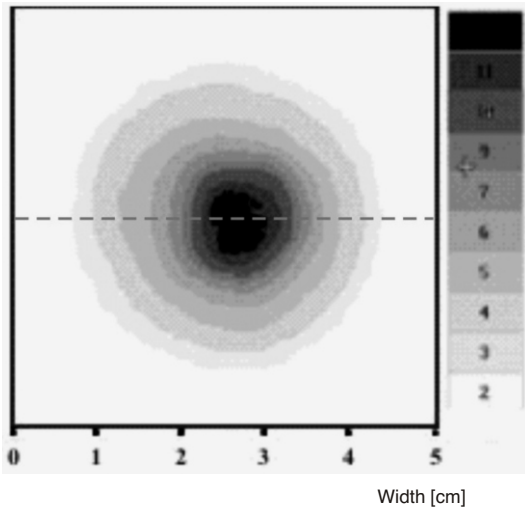

Figure 2. Absorbance of radiochromic film (5 5 cm) irradiated by EB as measured by microdensitometry and presented as a gray scale with twelve intensity levels. The dotted line shows the cross-section line used to obtain data in fig. 3

Table 1. The depth dose distribution of the total dose calculated for each film as a weighted average (by area) of doses for each segment

d [g/cm^2]	ΔP [mm^2]	$\Delta P/P$	A	D [kGy]	D_{tot} [kGy]
0	385.46 138.11 113.81 74.06 56.95 24.7 61	0.451 0.162 0.133 0.087 0.067 0.029 0.071	0.321 0.716 0.944 1.14 1.35 1.51 1.72	13.5	43 ± 2
0.057	545.9 130.71 41.04 31.15 31.2 68.89	0.643 0.154 0.048 0.037 0.037 0.081	0.267 0.793 1.06 1.23 1.46 1.88	10.8 ± 0.3 43 ± 1 64 ± 2 79 ± 2 101 ± 5 150 ± 12	35 1.7
0.114	650.62 101.13 31.26 15.98 64.89	0.753 0.117 0.036 0.018 0.075	0.294 0.783 0.932 1.24 1.51	12.2 ± 0.3 42 ± 2 53 ± 2 79 ± 2 106 ± 7	25 ± 1
0.171	691.15 102.64 59.88	0.81 0.12 0.07	0.254 0.713 1.36	10.2 ± 0.3 37 ± 1 91 ± 3	19.1 ± 0.6
0.228	758.36 36.91 67.85	0.879 0.043 0.078	0.212 0.727 1.06	8.2 ± 0.3 38 ± 1 64 ± 2	13.8 ± 0.4
0.285	794.19 70.5	0.918 0.082	0.184 0.915	6.9 ± 0.2 52 ± 2	10.6 ± 0.3
0.315	805.96 54.87	0.936 0.064	0.19 0.889	7.2 ± 0.2 50 ± 2	9.9 ± 0.3
0.345	834.51 30.87	0.964 0.036	0.163 0.869	5.9 ± 0.2 48 ± 2	7.4 ± 0.3
0.365	831.98 22.33	0.974 0.026	0.146 0.799	5.2 ± 0.2 43 ± 2	6.2 ± 0.2
0.422	852.94	1	0.124	4.2 ± 0.2	4.2 ± 0.2
0.479	857.34	1	0.082	2.4 ± 0.2	2.4 ± 0.2
0.536	845.24	1	0.051	1.2 ± 0.2	1.2 ± 0.2

ΔP – segment area; $\Delta P/P$ – fractional area; A – absorbance per segment; D – dose per segment; D_{tot} – dose per film

for determining the dose *vs*. penetration depth relationship for pulsed EB.

Figure 2 shows a typical result of microdensitometric measurements of absorbance of FWT-60 films irradiated with pulsed EB. Compared to the case of uniformly irradiated films, measurement of absorbance (and hence the dose) is not simple. Namely, the absorbance of certain central areas of the film (peak absorbance is close to 2) is within a nonlinear region of the calibration curve (see fig. 1), while peripheral regions are within the almost linear region (bellow 0.6), so the simple measurement of an average absorbance of the entire film would yield an erroneous value of the absorbed dose. We therefore used an image segmentation procedure. Concentric sections comprising of about 0.2 units of absorbance were identified, their average absorbance (corrected for the background absorbance) was determined and the dose for each

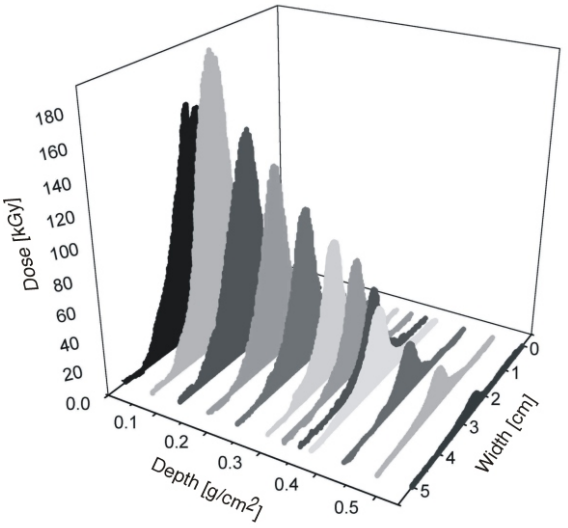

Figure 3. The depth-dose distribution measured by a stack of FWT-60 radiochromic films irradiated by pulsed EB. 2D dose profiles were given for the central cross section of the film

segment was calculated using data in fig. 1. Such procedure enabled correction for the nonlinear dosimeter response. The total dose for each film was then calculated as a weighted average (by area) of doses for each segment (tab. 1). Table 1 shows that the number of segments receiving the dose above the background value is progressively reduced, so that the 3D dose profile has a conical shape. In the last 3 films receiving low doses the segmentation is not necessary, but when absorbance is simply averaged without segmentation for the first few films, errors higher than 20% were found due to high optical density (OD) gradients.

Figure 3 shows the depth-dose distribution. Two-dimensional dose profiles of the central cross section of each film were obtained by point-by-point conversion of absorbance into doses using calibration data in fig. 1. The shape of the first profile in fig. 3 is slightly different from the others, which reflects the alteration of the beam geometry once electrons pass the first film and enter aluminum plates. In the very center of the beam, measured absorbancies are reaching values around 2.0, which is slightly higher then measured absorbancies shown in fig. 1, but using a polynomial fit they were converted into corresponding doses. In the case of uniformly irradiated films the error might be substantial, but it should be remembered that the overall dose of non-uniformly irradiated film was calculated per unit area (*i. e*., volume). Consequently, the area in the beam center that might exceed absorbance of 2.0 is so small (few square millimeters) so that contribution of uncertainties in converting these absorbencies into doses is less then 5% in the overall estimated error in dose calculation (tab. 1).

The above procedure is justified only if the calibration of dosimeters carried out at a gamma facility (dose rate around 1 Gy/s) can be transferred to EB irradiation (dose rate $>10^{11}$ Gy/s). It has been reported previously that FWT films have an almost identical response to both ^{60}Co and electron irradiation [9, 11] and that the response of FWT-60 is not dose rate dependent up to 10^{12} Gy/s [11]. The manufacturer even claims that the response is dose rate independent up to 10^{14} Gy/s, but they do not state how this was determined. Calorimetry, as a dose rate insensitive method, was used to verify that there is no rate dependence under our experimental conditions. Alanine dosimeters also appear to be dose rate independent up to 10^{11} Gy/s [12].

Image segmentation and correction for non-linear response of films also enables determination of the total dose received by the stack of dosimeters during the EB pulse. Using the energy absorbed per unit area F [2], comparison with calorimetry can be achieved as follows. The dose readings of individual samples of the stack enabled construction of the depth-dose distribution shown in fig. 4. In calculating the total dose for each film we used the area of 8.55 cm^2, *i. e.*, the aperture of the accelerator tube. This appears to be a reasonable choice since only the first film showed some absorbance beyond this area with values that were higher than the background value. However, by including these values, the overall calculated dose would be higher by only 1.6%. Integration of the depth-dose curve yielded a value of $F = 8.13$ J/cm^2. The total energy of the electron beam, as obtained from calorimetry, was 66.3 J. Using the same beam spot area of 8.55 cm^2, we obtained $F = 7.75$ J/cm^2. Such close agreement (the difference between the two techniques is only around 5%) demonstrates that microdensitometric scanning and the proper analysis of film OD gradients can yield an accurate

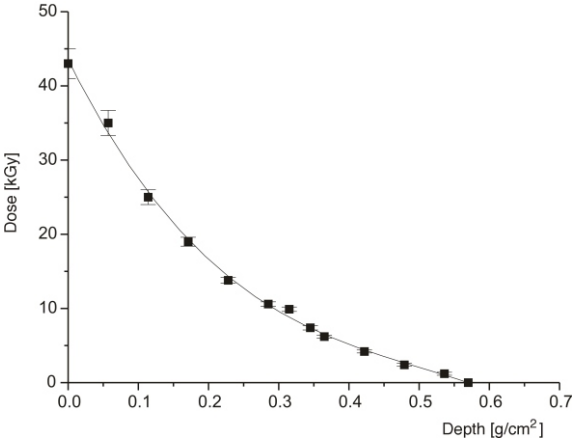

Figure 4. The depth-dose distribution of the total dose absorbed by a stack of FWT-60 radiochromic films irradiated by electrons

3D dose distribution even when a nonuniform irradiation of RCF is associated with their nonlinear response.

The above agreement might appear surprising since the response of the films can be temperature dependent [13, 14]. The heating of the films during pulsed EB irradiation is to be expected, which can afect the "transfer" of calibration that was carried out at a gamma facility. Using the average deposited energy per unit area of the beam spot (calorimetric measurements), the average temperature increase of the stack upon EB irradiation could amount to 16 °C. The maximum irradiation temperature is in first two films and can reach up to 50 °C. Effective irradiation temperature is therefore around 35 °C [14], *i. e.*, 15 °C above the room temperature (*i. e.*, the irradiation temperature at low dose rate gamma facility). In general, the absorbance in both radiochromic solution and in radiochromic thin films increases with temperature (in the region between 20 and 50 °C) approximately by 0.2% per degree Celsius [13-16]; this could increase the absorbance by not more than 3% and could not influence considerably our results. In addition, it has been found that the absorbance of irradiated FWT-60 films is temperature insensitive in the region between 20 and 50 °C [13]. Using plastic spacers instead of aluminum ones, the obtained F value was 7,66 J/cm^2 [17]. Slightly higher values of F obtained with aluminum spacers *vs*. plastic spacers can be a consequence of differences in thermal conductivity and/or electron scattering between these two materials, but for all practical purposes this differencies are negligible and are mainly determined by a minor differences in the output of the accelerator in separate irradiations.

Once the entire 3D data set is known, it is easy to determine the depth-dose distribution along any selected direction and for any selected area. A simple example is given in fig. 5. It demonstrates that almost identical results are obtained when the dose is evaluated using conventional spectrophotometry of 1 1 cm films and when it is extracted from the central 1 1 cm area of 5 5 cm films using the above described method. However, this agreement between spectrophotometry and scanning densitometry is due to the fact that practically no absorbance gradients exist within one square centimeter around the beam axis. The agreement of those results with EPR dosimetry further justifies the correctness of RCF dosimetry. However, it should be noted that it is almost impossible to determine the lateral distribution using EPR dosimetry (quantitative 2D or 3D EPR imaging is a very tedious procedure, [18]); thus the comparison of EPR and RCF dosimetry can be done only if scanning of the film shows no appreciable lateral absorbance gradients.

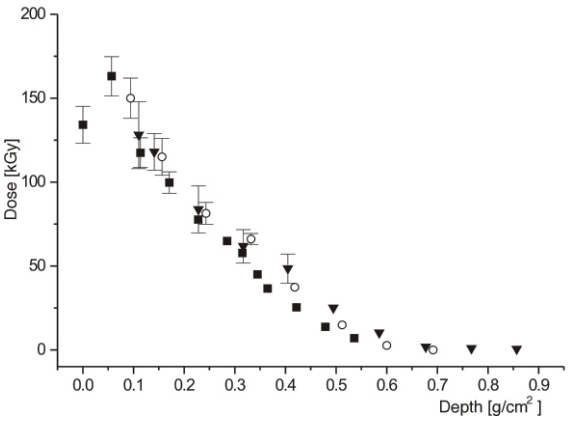

Figure 5. The depth-dose distribution in the central 1 1 cm area along the accelerator electron beam measured by: a stack of 5 5 cm FWT-60 radiochromic films (▪); a stack of 1 1 cm FWT-60 radiochromic films (○); a stack of 1 1 cm alanine film dosimeters (▾)

The depth-dose distribution curves in figs. 4 and 5 have different shapes and both are different from the theoretical depth-dose distribution for monoenergetic 2 MeV electrons. It is well known that the height of the maximum in the depth-dose distribution (due to the establishment of electron equilibrium) decreases with the increasing of the surface area of observation of the beam spot. Due to the necessity of comparison with calorimetric results, we had to deal with the total number of electrons and hence to scan a large area of the film. Therefore one can hardly expect a maximum on the depth-dose curve derived from those results. It is also the reason for the differences between the curves in figs. 4 and 5. Namely, electrons were not monoenergetic and not even near 2 MeV. Using data on 3D depth dose distribution, we were able to extract the initial electron energy spectrum [19], which is similar to a measured one using the same type of accelerator [20] indicating again usefulness and correctness of our 3D dosimetry measurements.

CONCLUSIONS

The use of RCF in assessing the 3D distribution of the absorbed dose has advantages due to their small thickness in stack configuration, ruggedness and ease of handling. However, when broad pulsed beams are examined, laser scanning of films OD seems mandatory for precise determination of the total dose absorbed by the film to account for nonuniform dose distribution followed by image segmentation which is important in case of nonlinear response of RFC. A calibration of the radiation response of RCF by means of both calorimetry and standard chemical dosimetry is advantageous. An adequate post-processing of 2D dose distribution of individual films enables determination of the depth dose distribution along any selected direction along the beam and for any selected cross section.

ACKNOWLEDGEMENTS

Dr. B. B. Radak had a crucial role in conducting calorimetric measurements. We are also grateful to him for valuable comments on the manuscript. This work was partially supported by the Ministry of Science and Environment Protection of the Republic Serbia (Projects 1969 and 1928).

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ТРОДИМЕНЗИОНАЛНА РАСПОДЕЛА ДОЗЕ У ПУЛСУ ЕЛЕКТРОНА ВИСОКЕ ЈАЧИНЕ ДОЗЕ – КОМБИНОВАНА МЕРЕЊА РАДИОХРОМНИМ ФИЛМОВИМА И КАЛОРИМЕТРОМ

Предложена је метода за прецизно и тачно одређивање тродимензионалне расподеле дозе коришћењем радиохромних филмова. Сендвич радиохромних филмова употребљен је за одређивање радијационог поља пулса електрона које производи акцелератор електрона јачине дозе око $5\ 10^{11}$ Gy/s и максималне дозе 160 kGy. Тродимензионална расподела дозе добијена је помоћу ласерског микродензитометра кориговањем на нелинеарни одговор радиохромних филмова помоћу сегментирања вредности апсорбанције филмова. Резултати мерења дозе радиохромних филмова упоређени су са резултатима мерења калориметром и помоћу електрон парамагнетне резонанције.