Applied Radiation and Isotopes 141 (2018) 112–117

Contents lists available at ScienceDirect

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso

The performance of a multi guard ring (MGR) diode for clinical electron beams dosimetry

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HIGHLIGHTS

- Performance of a multi guard ring structure (MGR) for clinical electron beam dosimetry.
- New type of diodes with enhanced tolerance to radiation is evaluated for electron dosimetry.
- Clinical electron beam dosimetry with semiconductor detector.

ARTICLE INFO

Keywords:
Clinical electron beam dosimetry
Semiconductor dosimeter
Radiation hard diode

ABSTRACT

The dosimetric response of a multi guard ring structure (MGR) diode has been studied with clinical electron beam energies from 5 MeV to 15 MeV. The results showed that the MGR dose response is linear in the range of 5–320 cGy and presents reproducibility with variation coefficients less than 0.4%. The field output factors measured with the MGR agreed within 2% with those measured with an ionization chamber. This study evidences that this diode can be used for clinical electron beam dosimetry.

1. Introduction

Radiotherapy treatments of superficial tumours with high energy electron beams from clinical linear accelerators have increased in the last two decades. Patient dose verification has been recommended for quality improvement of patient care in radiation therapy by several organizations (AAPM, 2005). According to the protocols of dosimetry, the electron beams calibration should be carried out in water with a parallel plate ionization chamber (IC). Nevertheless, the dose determination in narrow electron fields requires detectors with small volume, high sensitivity, energy independence and good mechanical stability. Silicon diodes with such characteristics are well established as dosimeters for photon and electron beam in radiotherapy treatments (Griessbach et al., 2005; Di Venanzio et al., 2013; Santos et al., 2014). However, ordinary silicon diodes are prone to radiation damage, which is responsible for the increase of the dark current, decay of its sensitivity with the accumulated dose and nonlinear instantaneous dose rate dependence for pulsed beams. New type of diodes with enhanced tolerance to radiation with multi guard ring (MGR) structure have been developed for applications in high dose and high energy physics (Candelori, 2006; Moll, 2006; Kramberger, 2007; Camargo et al., 2008). The aim of this paper is to study the response of a MGR diode for clinical electron beams dosimetry, by evaluating their dose and dose rate response, energy dependence and depth dose curve distribution in beam central axis.

2. Materials and methods

The MGR diode used in this work, with 4 mm^2 of active area, was processed out of 300 µm thick *n* type float zone substrate with a resistivity of about 3 kΩ cm. The frontal layer (p^+) of the diode was obtained by ion implantation, (Al/p + /n/n + /Al), and it comprises ten guard rings around the main junction. When unbiased, the device presents a leakage current of 6 nA and a capacitance of 3.8 pF (Camargo et al., 2007). To use this diode as a dosimeter, it was housed in an acrylic probe and covered with a thin black plastic layer in order to be

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https://doi.org/10.1016/j.apradiso.2018.07.002
Received 14 July 2017; Received in revised form 26 March 2018; Accepted 2 July 2018
Available online 03 July 2018

protected from light.

This probe was positioned at the centre of a PMMA plate with $30 \times 30\,cm^2$ and 1 cm thickness with its front face levelled with the surface of this plate. The diode was connected in the photovoltaic mode to the input of an integrating electrometer (Standard Imaging - model CDX 2000A). The response of the diode was evaluated with 6, 9, 12 and 15 MeV electron beams from a Varian Medical Systems Clinac 2100 C accelerator and with 5, 7, 8, 10, 12 and 14 MeV electron beams from a Siemens Primus Mid Energy accelerator, both of them collimated by the $10 \times 10\,cm^2$ electron cone applicator.

The value of the dose in water corresponding to each MU (Monitor Unit of the accelerator) was previously determined through the dosimetry with a parallel plate ionization chamber Scanditronix PPC05, connected to the electrometer CDX 2000A, and following the procedure described in the dosimetry protocol TRS-398 (IAEA, 2000). The calibration factor of the chamber for electron beam was achieved using the cross-calibration method with the reference chamber Farmer PTW 30013, as described in the protocol TRS-398.

2.1. Dose response

To investigate the dose response of the diode, the assembly constituted by the sensor and the PMMA plate was positioned at the centre of a $10 \times 10\,cm^2$ field, with the phantom surface at 100 cm from the source (SSD) on a phantom consisting of solid water slabs (Virtual Water D322). To provide the build-up, the PMMA plate with the photodiode was covered with Lucite slabs presenting appropriate thicknesses (Z_{ref}) for each electron beam energy. The plastic reference depth, $z_{ref\ pl}$, was obtained from the water reference depth, $z_{ref\ w}$, using Eq. (1) (IAEA, 2000):

$$z_{ref\ pl} = \frac{z_{ref\ w} \cdot \rho_w}{\rho_{pl} \cdot c_{pl}} \left(cm \right) \tag{1}$$

Where c_{pl} is a depth scaling factor, ρ_{pl} and ρ_w are the plastic and water density, respectively. In our study, the values are: $c_{pl} = 0.941\ g\,cm^{-3}$ and $\rho_{pl} = 1.19\ g\,cm^{-3}$.

All measurements were performed with dose rates of 320 cGy/min (Varian 2100C) and 300 cGy/min (Siemens Primus). Five consecutive measurements were carried out for each monitor unit value, within the dose range of 5–320 cGy. The combined uncertainty (u_C) of the results was calculated from the diode reading uncertainty ($u_{(\bar{M}_{Diode})}$), electrometer resolution ($u_{(Elet\ Res)}$), electrometer stability ($u_{(Elet\ Sta)}$) and accelerator stability ($u_{(Accel\ Sta)}$), in accordance with the Eq. (2) (IAEA, 2000):

$$u_{c(M_{Diode})} = \sqrt{(u_{(\bar{M}_{Diode})})^2 + (u_{(Elet\ Res)})^2 + (u_{(Elet\ Sta)})^2 + (u_{(Accel\ Sta)})^2} \tag{2}$$

The results obtained were fitted with the software Origin Pro 8.0 and analysed with respect to both linearity and sensitivity responses of the diode for electron beam energies from 5 to 15 MeV.

2.2. Response reproducibility

The reproducibility tests were performed with the diode positioned at Z_{ref} for each electron beam energy and at the centre of a $10 \times 10\,cm^2$ radiation field. With SSD of 100 cm and average dose rate of 300 cGy/min, ten consecutive measurements were carried out with electron energies of 6, 8, 9, 10, 12 and 15 MeV for the same radiation dose of 100 cGy.

2.3. Energy dependence

The energy dependence of the diode was evaluated through the values of the sensitivity coefficients obtained from the dose response calibration curves. Measurements were performed with electron beam energies within the range of 5–15 MeV. The sensitivity of the diode (nC/cGy) for each energy was normalised to that obtained with 12 MeV electron beam.

2.4. Average dose rate response

The diode response was investigated with the Varian 2100C accelerator for dose rates of 80, 160, 240 and 320 cGy/min. For these studies, the diode was positioned at the reference depth of 6 and 15 MeV electron beam energies and irradiated with a dose of 100 cGy. All measurements were performed with a $10 \times 10\,cm^2$ field size and 100 cm of SSD.

2.5. Field output factor

The output factor (OF) for 6 MeV electron beam of Varian 2100C accelerator was measured within the field size range from $6 \times 6\,cm^2$ to $20 \times 20\,cm^2$ with a 320 cGy/min average dose rate, a fixed dose of 100 MU and SSD at 100 cm. With the Siemens Primus Mid Energy, the diode was evaluated within the field size range from $10 \times 10\,cm^2$ to $25 \times 25\,cm^2$, 300 cGy/min average dose rate, 100 MU dose and SSD at 100 cm, for 5, 8 10, 12 and 14 MeV electron beams. The output field factors were normalised to the values at the $10 \times 10\,cm^2$ reference field. The results obtained with both accelerators were compared to those measured with an Advanced Markus PTW 34045 and a Scanditronix PPC05 ionization chambers. All measurements were carried out in the reference depth for each electron beam energy.

2.6. Central axis depth dose response

The percentage depth dose (PDD) response was determined for 6 and 15 MeV electron beams from Varian 2100 C accelerator. The plate containing the diode was placed in the centre of the electron beam, over a phantom made of PMMA slabs with different thicknesses. The PMMA thickness was converted into water thickness using the Eq. (1). The measurements were performed with diode depths ranging from 0 to 2.7 cm for 6 MeV, and from 0 to 7.0 cm for 15 MeV, keeping SSD at 100 cm. The phantom was irradiated at a $10 \times 10\,cm^2$ size field with a dose of 100 cGy and an average dose rate of 320 cGy/min. The percentage depth dose was calculated as the ratio between the diode reading at a given depth and the reading at the point of maximum dose. The values obtained were compared with those measured with the ionization chamber in the water phantom.

3. Results and discussion

3.1. Radiation dose response

Figs. 1 and 2 show the dose response of the MGR diode in the range of 5–320 cGy for measurements performed with the Varian 2100C and Siemens Primus Mid Energy accelerators, respectively. Each point corresponds to the average value of five measurements carried out with the MGR diode. The expanded uncertainty, $U_{(M_{Diode})}$, associated with each value is 0.8% for k = 2.

A linear fit of experimental data was performed by OriginPro 8.0 software providing the sensitivity, S, for each energy and the coefficient of correlation, R^2. The excellent results of R^2 indicate a linear behaviour in the range of the doses evaluated, as can be seen in Table 1.

The average sensitivity of the MGR diode is $10.9\ nC\,cGy^{-1}$ and the sensitivity per unit of volume is $27.3\ nC\,cGy^{-1}\,mm^{-3}$. Table 2 presents the comparison of the sensitivity per unit of volume of MGR diode with commercial dosimeters and two types of ionization chamber. These results show that the MGR diode exhibits sensitivity per unit of volume almost 70,000 higher than those obtained for the PPC05 and the Advanced Markus ionization chambers and at least twice over the sensitivity of the commercial photodiodes evaluated.

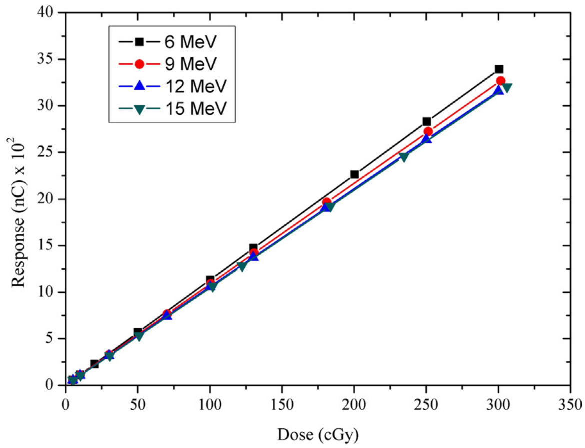

Fig. 1. Dose response of the MGR diode for 6, 9, 12 and 15 MeV electron beams from Varian 2100C accelerator.

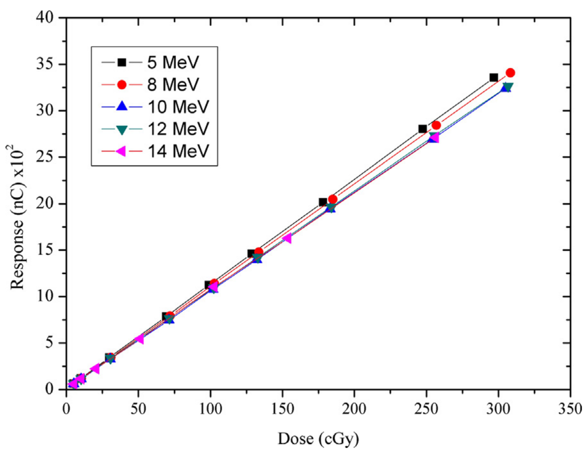

Fig. 2. Dose response of the MGR diode for 5, 8, 10, 12 and 14 MeV electron beams from Siemens Primus accelerator.

3.2. Reproducibility

The MGR diode results for ten consecutive measurements obtained with electron beam energies in the range of 5–15 MeV for a fixed dose of 100 cGy is shown in Table 3. The variation coefficient (VC), calculated by the ratio between the standard deviation (SD) and the average reading was less than 0.4%, which demonstrates an excellent reproducibility when compared to other commercial diodes using the same dose, as the Sun Nuclear QED diode, which reproducibility error for electrons was less than 0.5% (SUN NUCLEAR, 2017). Soriani et al. (2003) found a variation of less than 0.5% to ten successive measurements gathered with a Scanditronix SFD type p diode for 6 and 9 MeV electrons beams. The reproducibility of the diode MGR is better than the observed with the diode BPW-34, evaluated by Khoury et al. (1999) for electron dosimetry. The MGR diode results are also within the protocol AAPM TG-62 (2005) guidelines, which recommend a reproducibility error less than 1% for a diode used as a dosimeter.

3.3. Energy dependence

The energy dependence of the diode, evaluated through the values of the sensitivity coefficients as a function of the electron beam energy is presented in Fig. 3, normalised to the sensitivity coefficient obtained for 12 MeV. The results show that the maximum variation of 6.9% was obtained with 6 MeV electron beam.

3.4. Average dose rate response

Fig. 4 presents the relative response of the MGR diode irradiated with 6 and 15 MeV at 100 cGy as a function of the average dose rate ranging from 80 to 320 cGy/min. The values on the graph are the ratio of the MGR diode readings at any average dose rate to those gathered at 80 cGy/min. As can be seen, for both electron beam energies the variation of the relative response of the diode is less than 0.15% and, therefore, being almost independent on the average dose rate covered in this work.

3.5. Field size response

Output field factors, defined as the ratio between the measurement in the X cm x Y cm field of interest and that performed in the 10 × 10 cm^2 reference field with the same irradiation dose, were calculated based on the MGR diode responses for different cone applicator sizes. The OF values of 6 MeV electron beams (Varian 2100C accelerator) and for 5, 8, 10, 12 and 14 MeV electrons (Siemens Primus accelerator) were normalised to those obtained with the Advanced Markus ionization chamber in the 10 × 10 cm^2 field size. The results are presented in Fig. 5, which evidences that the output field factors found with the diode agree within 2% with those accessed with the ionization chamber. This result is consistent with those from Eveling et al. (1999) for the Scanditronix EDD-2 diode.

3.6. Central axis depth dose response

Figs. 6 and 7 show the percentage depth dose (PDD) curves of 6 MeV and 15 MeV electron beams measured with the MGR diode at 10 × 10 cm^2 field size. The depth is expressed in terms of water, calculated by taking into account the densities of PMMA and water itself. In the two energies evaluated, the PDD profiles obtained with the MGR diode agree with those taken with the ionization chamber for depths greater than the depth of dose maximum. Conversely, in the build-up region, the data gathered with the diode underestimate the surface dose up to 15% (6 MeV) and 10% (15 MeV). Despite of being more pronounced in the MGR diode, this shift in the PDD curves toward lower values of dose has been also found by Shortt et al. (1986) with p-type

Table 1
Sensitivity coefficient values and calibration equation curves with corresponding R^2 coefficients for the MGR diode irradiated with different electron energies.

Linear Accelerator	Energy (MeV)	Calibration curve equation	R^2	Sensitivity (nC cGy^{-1})
Varian 2100C	6	y(nC) = 11.31·x (cGy)	0.9999	11.31
	9	y(nC) = 10.85·x (cGy)	1.0000	10.85
	12	y(nC) = 10.58·x (cGy)	0.9999	10.58
	15	y(nC) = 10.47·x (cGy)	0.9999	10.47
Siemens Primus Mid Energy	5	y(nC) = 11.51·x (cGy)	0.9989	11.51
	8	y(nC) = 11.20·x (cGy)	0.9991	11.20
	10	y(nC) = 10.72·x (cGy)	0.9991	10.72
	12	y(nC) = 10.90·x (cGy)	0.9982	10.90
	14	y(nC) = 10.84·x (cGy)	0.9990	10.84

Table 2
Summary of the sensitivity normalised to the sensitive volumes of commercial and MGR detectors.

Diode	Energy (MeV)	Sensitive Volume (mm^3)	Average Sensitivity ($nC\,cGy^{-1}$)	Mean Sensitivity Normalised ($nC\,cGy^{-1}\,mm^{-3}$)	Reference
MGR	6–15	0.4	10.9	27.3	This work
QED Sun Nuclear	4–25	0.04	0.32	8	(SUN NUCLEAR, 2017)
ISORAD Sun Nuclear		0.07	0.27	3.9	(SUN NUCLEAR, 2017)
EDD-2 Electron Scanditronix		0.19	0.25	1.3	(SCANDITRONIX, 2017)
EFD Electron Scanditronix		0.19	0.25	1.3	(SCANDITRONIX, 2017)
SFD Stereotactic Scanditronix		0.017	0.25	14.7	(SCANDITRONIX, 2017)
Advanced Markus PTW34045 IC	4–45	20	7×10^{-3}	3.5×10^{-4}	(PTW, 2017)
Scanditronix PPC05 IC		50	2×10^{-2}	4×10^{-4}	(SCANDITRONIX, 2017)

Table 3
Mean response of the MGR diode with its standard deviation and variation coefficient at 100 cGy for electron beam energies of 5–15 MeV.

Linear Accelerator	Energy (MeV)	Mean Response (nC)	Standard Deviation (nC)	Coefficient of Variation (%)
Varian 2100 C	6	1131.5	0.9	0.08
	9	1092.2	0.4	0.04
	12	1057.5	1.4	0.13
	15	1064.9	0.6	0.06
Siemens Primus Mid Energy	5	1122.1	1.5	0.13
	8	1136.9	0.9	0.08
	10	1078	3	0.30
	12	1094	3	0.28
	14	1089	4	0.37

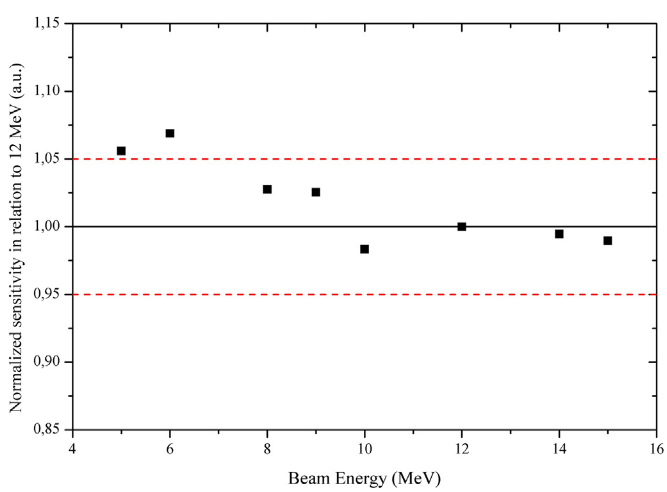

Fig. 3. Sensitivity of the MGR diode for 5, 6, 8, 9, 10, 12, 14 and 15 MeV electron beams normalised to 12 MeV electrons.

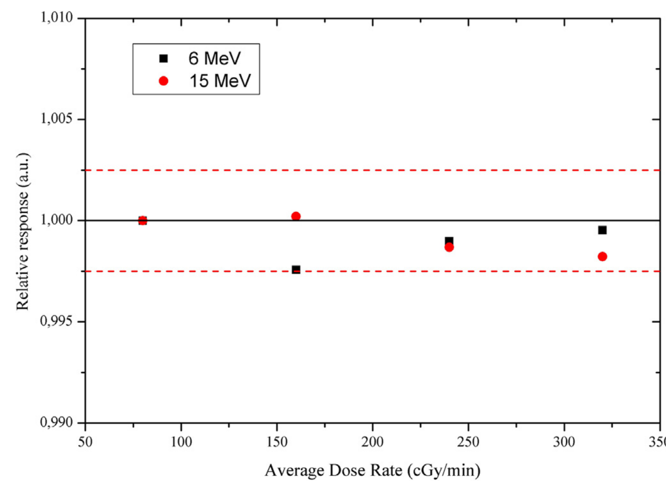

Fig. 4. Relative response of the MGR diode irradiated with 6 and 15 MeV electron beams as a function of the average dose rate. The MGR diode readings are normalised to those measured at 80 cGy/min.

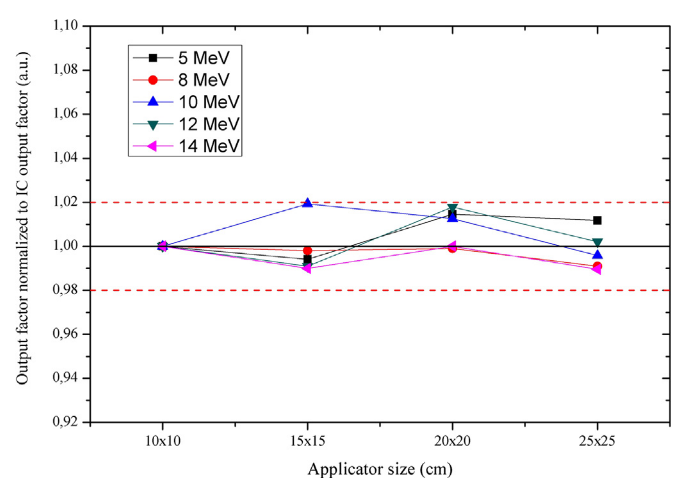

Fig. 5. Output field factors measured with the MGR diode for different square field sizes in the range of 5–14 MeV electron beams. The data were normalised to those obtained with the Advanced Markus ionization chamber in the $10 \times 10\,cm^2$ field size.

diode, Song et al. (2006) with a Scanditronix EFD diode, Scherf et al. (2009) and Griessbach et al. (2005) using shielded/unshielded PTW 60008/60012 diodes. Based on these data and our previous results (Khoury et al., 2007), it seems that the under-response of the MGR diode might be due to the combination of the electron energy loss in the dead layer of the unbiased diode and the influence of the decrease in the silicon to water mass stopping power ratio on the raw readings accessed with the MGR device. To quantify these effects, the energy loss was calculated by using the data base ESTAR from NIST (2018) taking into account the energy of the electron beam and the dead zone of the diode comprised by Al (2 nm), SiO_2 (650 nm) and p^+ (300 nm) layers. From these calculations, considering the beam monoenergetic and neglecting the effect of electron scattering, the energy loss of 6 MeV and 15 MeV electrons amounted to 1.5% and 0.9%, respectively. Additionally, the contribution of the second effect in the build-up region was weighted by correcting the raw readings gathered with the diode for the ratio of the mass stopping power of silicon to that of water using the data base ESTAR. The results pointed to differences between the PDD data with and without stopping power corrections up to 3.5% for 6 MeV and less than 0.5% for 15 MeV electrons. As can be seen, the previous effects are mainly significant for 6 MeV electron beams where, indeed, most of the electrons have energy lower than 5 MeV. Despite of being a rough estimation, it is clear that the under-response of the MGR

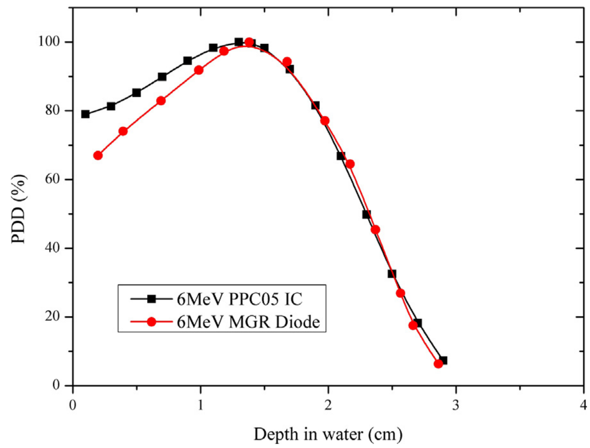

Fig. 6. Percentage depth dose (PDD) of 6 MeV electron beam measured in water with the MGR diode and the ionization chamber Scanditronix PPC05.

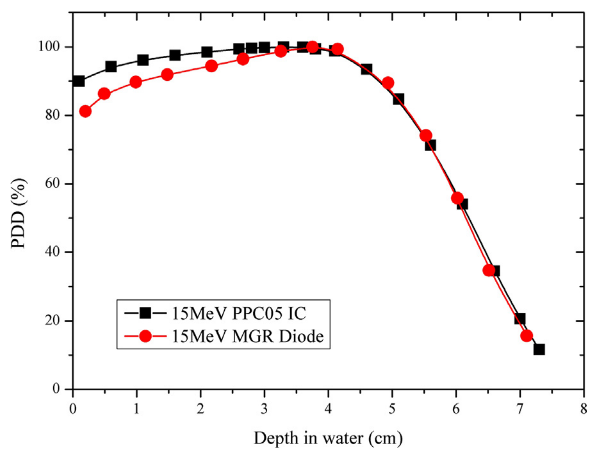

Fig. 7. Percentage depth dose (PDD) of 15 MeV electron beam measured in water with the MGR diode and the ionization chamber Scanditronix PPC05.

Table 4
Mean energy of the electrons at the phantom surface (E_0), practical range (R_p) and half-value depth (R_{50}) obtained with the MGR diode and the PPC05 ionization chamber for electron beams of 6–15 MeV.

Nominal Beam Energy (MeV)	MGR Diode			Ionization chamber PPC05		
	R_{50} (cm)	R_p (cm)	$\overline{E}_0$ (MeV)	R_{50} (cm)	R_p (cm)	$\overline{E}_0$ (MeV)
6	2.28	2.83	5.46	2.28	2.85	5.46
15	6.15	7.5	14.15	6.20	7.55	14.27

diode in comparison with the results accessed with the ionization chamber could be only partially explained by the superposition of these both effects. Theoretically, there are several factors such as real electron beam energy spectrum, angular dependence of the diode due to its complex structure and presence of materials with different densities, that acting together may introduce errors in the measurements performed in the build-up region. Quantify the contribution of all these effects require hard Monte Carlo simulation, which is beyond the scope of this work. However, it is worth pointing out that these results in the build-up region and the good agreement hereby achieved for depths greater than the depth of dose maximum in the PDD curves, where the ionization chamber is indeed considered as a gold standard, are consistent with the recommendations of the AAPM-TG51 (1999).

The mean energy of the electrons at the phantom surface (E_0), the practical range (R_p) and the half-value depth (R_{50}) were estimated from Fig. 7 and 8. The value of E_0 was obtained based on the relationship from the IAEA/TRS-381 (IAEA,1997):

$$E_0 = 0.656 + 2.059\, R_{50} + 0.022\, R_{50} \quad (3)$$

Table 4 presents the results of the mean energy of the electrons at the phantom surface (E_0), the practical range (R_p) and the half-value depth (R_{50}) obtained with the ionization chamber and the MGR diode. The values of R_p were calculated by extrapolation of the dose depth percentage curve. The results show that the values obtained with the MGR diode agree with those obtained with the ionization chamber, with an error smaller than 0.7%, comparable to the uncertainty values.

4. Conclusions

The dosimetric response of a rad hard silicon MGR device was investigated with clinical electron beam energies from 5 M to 15 MeV in the dose range of 5–320 cGy. The response of the diode to dose evidenced a linear behaviour with an excellent reproducibility characterized by variation coefficients less than 0.4%. The studies about the energy dependence of the diode showed that it was within 2% for 10–15 MeV and 7% for 5 MeV electron beams. Furthermore, the field output factors measured with the MGR device agreed in 2% with those measured with the ionization chamber. Nevertheless, the use of the MGR diode for electron depth-dose profiles should be restricted for depths beyond the depth of maximum dose where the better agreement with the results gathered with ionization chamber was found. Objectively, the degree of this agreement holds with the practically identical values of depths of 50% of dose and practical ranges hereby achieved by the MGR diode and the ionization chamber. All these results prove that this MGR diode can be used as an alternative detector for clinical electron beam dosimetry.

Acknowledgments

The authors thank Liga Norte-Rio-Grandense Contra o Câncer – Natal RN / Brazil and the Santa Casa de Misericordia - Itabuna-BA/ Brazil for leaving at our disposal the accelerators facilities. They also thank the National Research Council (CNPq) (305903/2011-0 and 310668/2012-3) for financial support.

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