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Characterization of a commercial PIN diode for radiotherapy photon beam dosimetry

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ABSTRACT

The dosimetric characterization of a commercial diode (BPW-34) was performed using a True Beam accelerator (Varian), with flattening filter (FF) photon beams of 6 and 15 MV and flattening filter free (FFF) of 6 MVFFF. The main performance characteristics, namely dose response, energy and dose rate dependence, field output factor, and percentage depth dose profile (PDD), were compared with those available in the literature and, whenever possible, benchmarked against the Varian Eclipse treatment planning system (TPS) predictions. Regardless of the energy, the results showed that the dose response curves are linear ($R^2 = 1$) with nonlinearity parameters less than 0.1% and 0.3% of repeatability. Furthermore, the average dose rate effect (0.7%) is almost negligible within the range of 20–600 MU/min (6 MV, 15 MV) and 400–1400 MU/min (6 MVFFF). Despite these good results, the charge sensitivity measurements evidenced that the diode response depends slightly on the energy, being within 5% for 6 MV–15 MV. It is important to underline that all these results adhere to the standard radiotherapy dosimetry protocols. Moreover, the general output field factor measurements and the percentage depth dose profiles, which are in excellent agreement with the Eclipse TPS calculations, also demonstrated that the diode BPW-34 is a low-budget alternative radiotherapy photon beam dosimeter.

1. Introduction

The development of accelerators that feature high technology and modern radiotherapy techniques such as Intensity Modulated Radiation Radiotherapy (IMRT), Volumetric Modulated Arc Therapy (VMAT), Stereotactic Radiosurgery (SRS), and Stereotactic Body Radiotherapy (SBRT) has allowed for a reduction in the irradiation field, enabling to treat small lesions with well-defined locations and limits. Treatment safety requires high precision in delivering the dose to the patient to guarantee a greater dose concentration in the target volume, saving the healthy tissues and surrounding organs at risk as much as possible. The effectiveness of such therapeutic purposes depends on the uncertainties associated with the treatment planning process and the clinical beam performance parameters. Therefore, dosimetry plays a key role in all quality assurance programs established to comply with the recommendations of the standard dosimetry protocol AAPM 87- TG62 (2005). The ideal dosimeter to cope with the increasing complexity of IMRT and VMAT treatment methods encompassing small field sizes, high-dose gradients, and varying energy and rate intensities is based on silicon diodes. They offer attractive qualities as a dosimeter, such as high spatial resolution, linearity, high radiation sensitivity, and real-time readout, which allows for in vivo dosimetry. For this reason, several dosimetry systems based on silicon diodes have been used in vivo dosimetry (Jornet et al., 2000; Saini and Zhu, 2007; Alaei et al., 2009; Islam et al., 2014) and to evaluate clinical photon, electron, and proton beam dosimetric features (Dixon and Ekstrand, 1982; Rikner and Grussel, 1987; Khoury et al., 1999, 2007; Saini and Zhu, 2004; Casati et al., 2005; Griessbach et al., 2005; Bruzzi et al., 2007; Gonçalves et al., 2014; Santos et al., 2014; Nascimento et al., 2018). However, due to their small volume, high sensitivity, and fast response time compared to ionization chambers, silicon diodes have also proven to be very suitable for small-field dosimetry (Haryanto et al., 2002; Das et al., 2008;

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Aspradakis et al., 2010; Bassinet et al., 2013; Santos et al., 2014).

This work investigates the dosimetric features of commercial diodes (BPW-34) for radiotherapy photon beam dosimetry by evaluating their dose response, energy and dose rate dependence, field output factor, and percentage depth dose profile (PDD). The experimental results are compared with those available in the literature and, whenever possible, benchmarked against Varian Eclipse treatment planning system (TPS) predictions.

2. Materials and methods

The commercial PIN photodiode, BPW-34 supplied by Osram, was manufactured in planar technology with an active area of 7.45 mm^2. The diode was covered with a black resin and connected in the photovoltaic mode to an integrating electrometer (PTW, Unidos E model) to be used as a dosimeter. The diode was placed in the center of a PMMA plate 30 × 30 cm^2 and 1 cm thick, with its front face leveled with the plate surface set at a depth of 10 cm in a 30 cm thick solid water phantom.

The dosimetric characterization was performed using a Varian True Beam 1762 accelerator, located at the Real Hospital Português de Beneficência (Recife/PE), with flattening filter (FF) photon beams of 6 and 15 MV, flattening filter free (FFF) of 6 MV, and a radiation field of 10 cm × 10 cm. For clarity, throughout the article, the flattening filter-free beam of 6 MV is named 6 MVFFF. Keeping constant the phantom surface at 100 cm from the source (SSD), the measurements were carried out with dose rates of 600 MU/min for photons of 6 MV and 15 MV and 1400 MU/min for those of 6 MVFFF.

2.1. Response repeatability and charge sensitivity

Response repeatability was evaluated with the diode positioned at a depth of 10 cm to the solid water phantom and in the center of the 10 × 10 cm^2 field. With an SSD of 100 cm, five consecutive measurements were performed by switching on and off the 6 MV, 15 MV, and 6 MVFFF photon beams for the same dose of 1.0 Gy. The results were evaluated through the average, standard deviation, and coefficient of variation of the charge generated in the diode-sensitive volume.

The diode sensitivity dependence on the photon beam energy for 6 MV, 15 MV, and 6 MVFFF was also evaluated through the variation in its response, given by the charge per unit dose (nC/Gy), assessed from the corresponding dose response curves.

2.2. Dose-response

The dose response curves of the diode were investigated for 6 MV, 15 MV, and 6 MVFFF, measuring the charge produced versus the radiation dose. Each point on the specific curve averages three consecutive readings taken for each monitor unit value covering a dose range of 0.2–4.0 Gy. The results were fitted with Origin Pro 8.0 and analyzed concerning the diode linearity and sensitivity responses. To check whether the diode response was dose rate dependent, three irradiations to 0.4 Gy were consecutively performed at different dose rates between 20 and 600 MU/min for 6 and 15 MV, 400 and 1400 MU/min for 6 MVFFF. The accelerator was calibrated to deliver 1 cGy/MU at the maximum dose depth in water at a source-to-surface distance (SSD) of 100 cm for all energies. The result obtained with the BPW-34 diode was compared with the dose value previously measured with an ionization chamber in the same geometry. To ensure the stability of the detector, each set of 10 (ten) measurements was read for a dose of 100 cGy, and the value was compared with the previous readings.

2.3. Output factor

The output field factors (OFF) for photons of 6 MV, 15 MV, and 6 MVFFF were measured within the field size range from 1 × 1 cm^2 to 20 × 20 cm^2 under fixed irradiations to 75 MU with dose rates of 600 MU/min (6 MV, 15 MV) and 1400 MU/min (6 MVFFF). Two readings were recorded for each field size, and the corresponding OFF values normalized to that found at the 10 × 10 cm^2 reference field. The results were compared with the values predicted by the Eclipse planning system data. The results were compared with the values predicted by the Eclipse planning system data and the results of measurements taken with Sun Nuclear Corporation commercial EDGE diode, model 1118, using the same experimental setup. The EDGE Detector is a radiation detector with a very small active area and volume and is precise in measuring small photon beams.

2.4. Percentage depth dose

The percentage depth dose (PDD) response was determined for 6 MV, 15 MV, and 6 MVFFF, with the plate containing the diode placed over a phantom made of PMMA slabs of different thicknesses. The measurements were performed with diode depths ranging from 0 to 16 cm, keeping SSD at 100 cm (Fig. 1a). The phantom was irradiated at a 10 × 10 cm^2 size field to 0.75 Gy with dose rates of 600 MU/min (6 MV, 15 MV) and 1400 MU/min (6 MVFFF). 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 (Fig. 1b). The values obtained were compared with those assessed for the Eclipse treatment planning system commissioning and validated by the accelerator manufacturer data. The values are compared with those obtained with the commercial diode EDGE detector.

3. Results and discussion

3.1. Response repeatability

Table 1 shows the coefficient of variation (CV) of the diode response

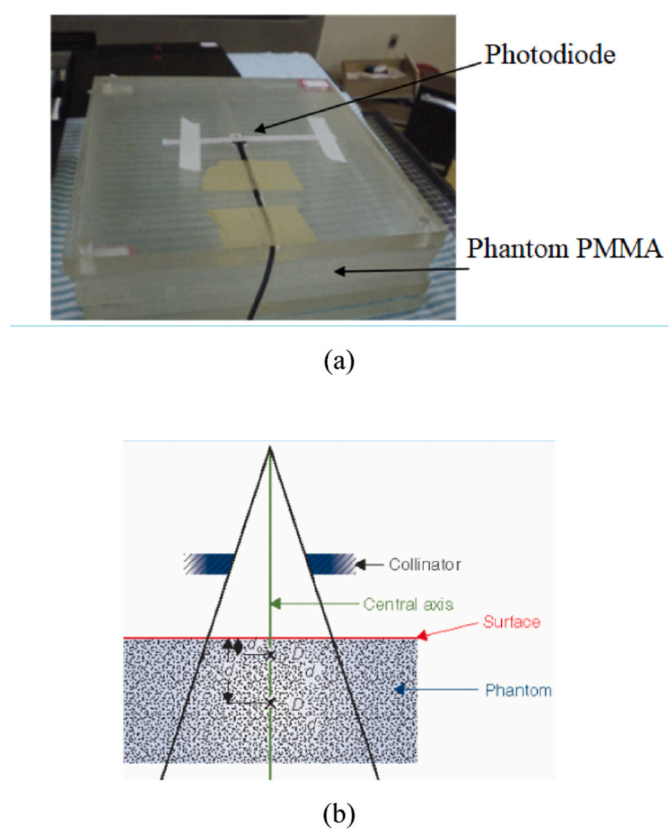

Fig. 1. (a) Measurement setup with diode depths ranging from 0 to 16 cm and (b) PDD scheme as from Khan and Gibbons (2014).

Table 1
Repeatability and charge sensitivity factors of 6 MV, 15 MV, and 6 MVFFF photons. The sensitivity errors come from the linear fitting of the corresponding dose response plots (Fig. 2).

Radiation Beam	Repeatability – CV (%)	Charge Sensitivity (nC/Gy)
6 MV	0.3	1303.55 ± 0.23
15 MV	0.2	1236.0 ± 0.6
6 MVFFF	0.2	1302.41 ± 0.06

for five consecutive measurements carried out with a dose of 1.0 Gy for photon beams of 6 MV, 15 MV, and 6 MVFFF. The results show that the CV is less than 0.3%, which aligns with AAPM 87-TG62 (2005) recommendations that it should be less than 1%. This result is similar to or better than those attained with several diodes as, for example, the BARC PIN diode with a CV of 0.5% for photons of 6–18 MV (Kumar et al., 2014).

3.2. Dose-response

Fig. 2 shows the charge generated in the diode sensitive volume as a function of the absorbed dose within the 0.2–4.0 Gy range. Each point corresponds to the average of three measurements for 6 MV, 15 MV, and 6 MVFFF. The maximum standard deviation of the measurements was 0.6%, which is too small to be represented on the graph. The results show that the curves for 6 MV and 6 MVFFF energies present the same response. For 15 MV, there is a small variation in the angular coefficient of the straight line, indicating a small energy dependence in the detector response, around 5%.

This energy dependence is almost equal to that found (2–5%) with a PIN diode (BARC) irradiated by photons between 6 MV and 18 MV, taking as reference the gamma rays from ^{60}Co (Kumar et al., 2014). Using the same method, Saini and Zhu (2007) investigated several commercial diodes (Nuclear Associates, Scanditronix, and Sun Nuclear) for photon dosimetry covering the 6–18 MV range. They observed significant variation (2%–39%) in their responses as a function of energy compared to that attained with the gamma rays from ^{60}Co. From this comparison with commercial devices, 5% of energy dependence achieved for the BPW-34 diode is reasonable and does not prevent them from using in radiotherapy services.

About the sensitivity of the BPW-34 diode response, the data in Table 1 shows that it is in the order of 1300 nC/Gy for 6 MV and 6 MVFF photon beams and 1236 nC/Gy for 15 MV. It is higher than the EDGE detector, model 1118, which is 32 nC/Gy.

Table 2 shows the normalized sensitivity (nC.cGy^{-1}.mm^{-3}) of the photodiode BPW-34 compared to commercial diodes used in radiotherapy dosimetry. BPW-34 presents excellent sensitivity and produces more charge per cGy per mm^3 than the commercial diodes used in radiotherapy clinics.

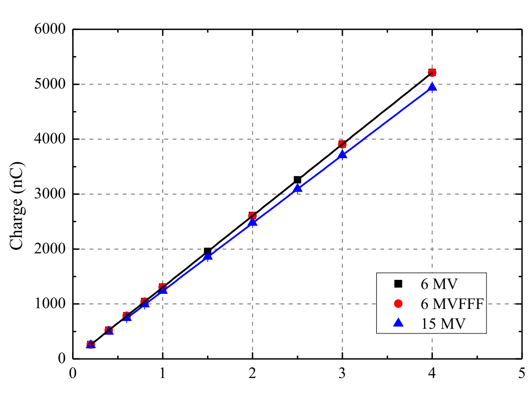

Fig. 2. Dose response of the BPW-34 diode for 6 MV, 6 MVFFF, and 15 MV photons from Varian True beam 1762 accelerator.

Table 2
Charge sensitivities and normalized sensitivities for commercial diodes and BPW-34 for different photon radiation energies.

Detector	Radiation Beam	Sensitive volume (mm^3)	Sensitivity (nC.cGy^{-1})	Normalized Sensitivity (nC.cGy^{-1}. mm^{-3})	Ref.
Diode p 60016	^{60}Co-25 MV	0.03	0.09	3	PTW (2023)
QED	1–25 MV	0.04	0.32	8	Sun Nuclear (2023)
ISORAD	1–25 MV	0.07	0.27	3.86	Sun Nuclear (2023)
EDGE	1–18 MV	0.019	0.32	16.85	Sun Nuclear (2023)
PFD^{3G}	1–20 MV	1.76	35	19.88	IBA Dosimetry (2023)
BPW-34	6 MV 15 MV 6 MVFFF	0.44	13.03 12.35 13.02	29.61 28.07 29.59	**This Paper**

3.3. Dose rate dependence

Fig. 3 shows the response of the diode to a dose of 0.4 Gy, obtained at different dose rates, normalized to the value obtained at a rate of 600 MU/min, which is most commonly used in routine treatments. The corresponding value of 1MU/min to the dose rate is 1 cGy/min. For the 6 MV and 15 MV beams, measurements were made at 20 and 600 MU/min dose rates, and for the 6 MVFFF at 400 and 1400 MU/min.

The AAPM 87-TG62 (2005) protocol recommends assessing dependence on the average dose rate based on the ratio between the average readings of the maximum and minimum dose rates, keeping the monitor dose of 100 MU constant. Table 3 presents the results obtained with the BPW-34.

The BPW-34 response complies with AAPM recommendations, which establish that the ratios must be between 0.98 and 1.02.

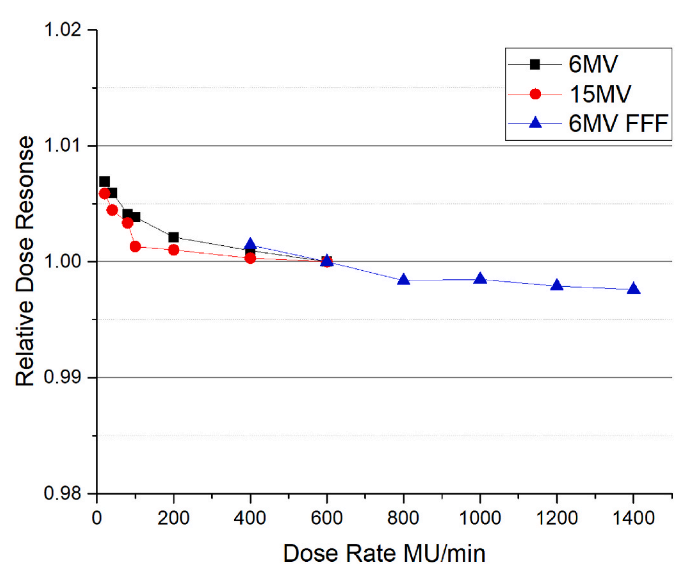

Fig. 3. Relative response of the BPW-34 diode for 6 MV, 6 MVFFF, and 15 MV photons as a function of the average dose rate. The diode readings are normalized to those measured at 600 MU/min, mostly used in routine treatments.

Table 3
Response of the BPW-34 diode to a dose of 0.4 Gy at different dose rates, normalized to the value obtained at a rate of 600 MU/min.

Radiation Beam	Response
6 MV	0.990
15 MV	0.994
6 MVFF	0.996

3.4. Output field factor (OFF)

Figs. 4–6 show the OFF results for photons with energies of 6 MV, 15 MV, and 6 MVFFF, respectively, using field sizes from 1 × 1 cm^2 to 20 × 20 cm^2. The data assessed with the Eclipse treatment planning system (TPS) and the commercial diode, EDGE, model 1118, was plotted in the graphics for comparison. The Eclipse treatment planning system uses the algorithm AAA (Analytical Anisotropic Algorithm) and a voxel size of 0.1 cm. The EDGE diode results were corrected according to the factors provided by TRS 483 for small fields (IAEA, 2017).

The results show that the OFF values increase for larger field sizes due to the scattering contribution to the absorbed dose at all energies. Furthermore, there is a good agreement between the experimental data obtained with BPW-34, EDGE detector and the values predicted by the Eclipse TPS, with variation lower than 1% for field sizes from 5 × 5 cm^2 to 15 × 15 cm^2 and 2% for larger fields up to 20 × 20 cm^2. For field sizes smaller than 5 × 5 cm^2 the BPW-34 response reaching 3.4% for 1 × 1 $cm^{2,}$ for photon beam of 6 MV and 2.3% for 15 MV, while the diode EDGE showed a variation of 2.8% for the field size of 1 × 1 cm^2 for 6 MV beam and of 5.7% for 15 MV, and of 0.5% for the other field size. Uncertainties in the output factors can lead to inaccuracies in the dose planned for the patient and that, in the case of BPW, it is not suitable for dosimetry of field size smaller than 5 × 5 cm^2, and the commercial diodes have correction factors for small fields to reduce these errors, published in the TRS 483.

Similar results, i.e., higher differences for smaller fields and lower differences for field sizes larger than 4 × 4 cm^2, are obtained by Haryanto et al. (2002) and Das et al. (2008). Regarding small fields, especially for 1 × 1 cm^2, almost a 5% difference in the datasets acquired by various diodes is reported in the literature (Bassinet et al., 2013; Santos et al., 2014). OFF data's great inaccuracy in a 1 × 1 cm^2 field comes from the lack of lateral charged particle equilibrium, partial occlusion of the source focal spot by the collimators, and differences among energy spectra in small and regular field sizes. For this reason, there is no standard dosimeter for field sizes of about 1 × 1 cm^2 (Aspradakis et al., 2010).

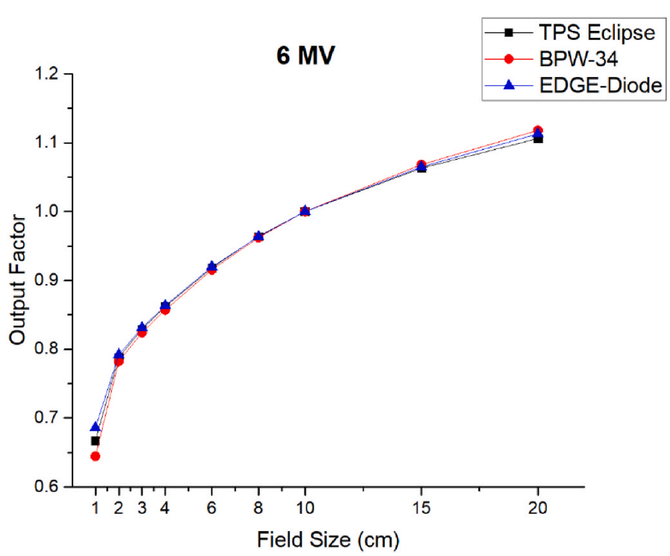

Fig. 4. OFF measurements carried out for photons with energies of 6 MV using field sizes from 1 × 1 cm^2 to 20 × 20 cm^2.

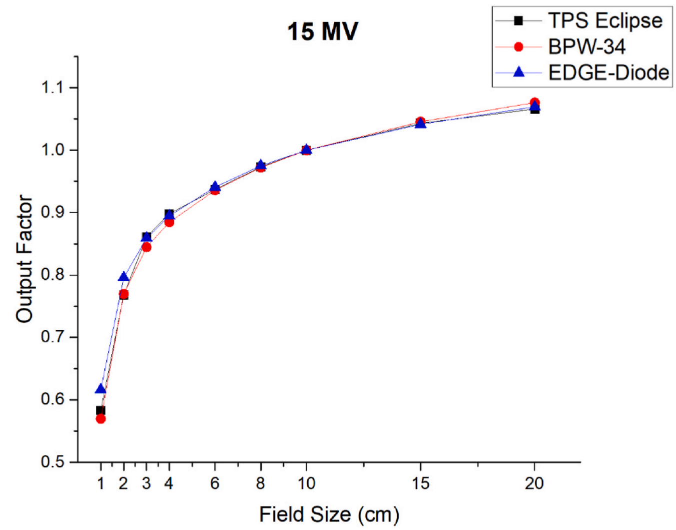

Fig. 5. OFF measurements carried out for photons with energies of 15 MV using field sizes from 1 × 1 cm^2 to 20 × 20 cm^2.

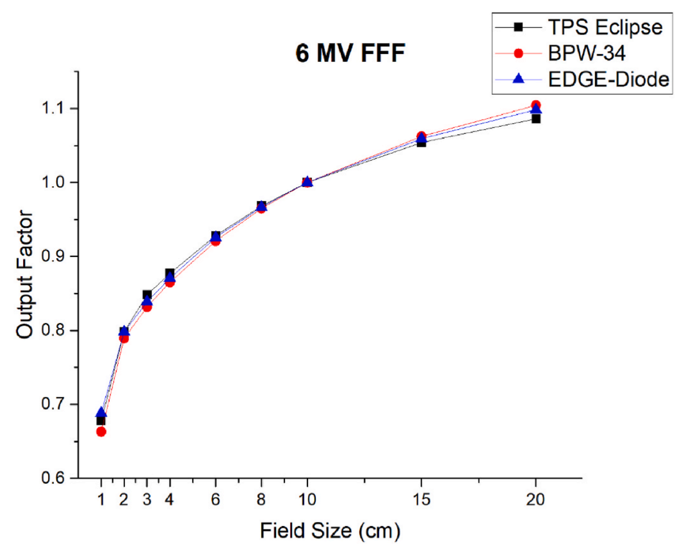

Fig. 6. OFF measurements carried out for photons with energies of 6 MVFFF using field sizes from 1 × 1 cm^2 to 20 × 20 cm^2.

3.5. Percentage depth dose profiles

Fig. 7 a, b, and c show the percentage depth dose (PDD) curves of (a) 6 MV, (b) 15 MV, and (c) 6 MVFFF photon beams measured with the BPW-34 diode and EDGE detector centered at 10 × 10 cm^2 field size. The experimental data are plotted with the theoretical values predicted by the Eclipse treatment planning system based on the Monte Carlo code. The results showed a good agreement between the data obtained with both diode detectors. Regardless of the photon energies, the experimental data and the Eclipse TPS calculations match better than 2%. In particular, the PDD profiles of 6 MV and 6 MVFFF show deviations less than 1% for depths spanning from 1.5 to 10 cm and almost 2% for greater depths, likely due to the increased contribution of the scattered radiation. For the 15 MV photon beam, the differences between experimental and theoretical PDD values remained within 2% for depths

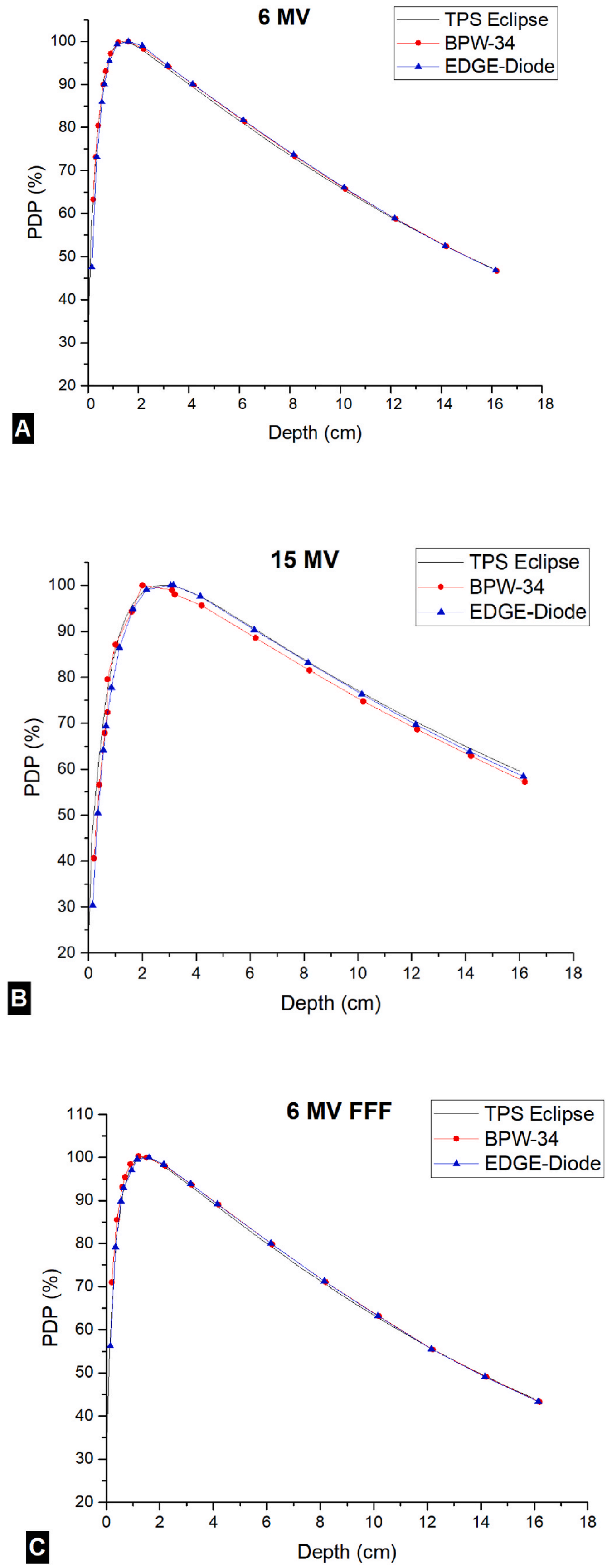

Fig. 7. - Percentage depth dose (PDD) profiles of (a) 6 MV, (b) 15 MV, and (c) 6 MVFFF photons gathered with the BPW-34 and EDGE diodes. The theoretical values from the Eclipse treatment planning system are shown for comparison.

above the buildup region.

The gamma index is an alternative method for the comparison between measured and calculated dose distributions. This method has become the gold standard for the comparison between measured and calculated dose distributions (Tai et al., 2017). Using the ScanDose Match software it was possible to plot chart gamma index with the PDP curves obtained with the BPW-34 for the photons beams from 6 MV, 15 MV and 6 MVFFF. Fig. 8 a, b, c shows the percentage depth dose (PDD) curves of (a) 6 MV, (c) 6 MVFFF, (gamma 1%, 1 mm) and (b) 15 MV (gamma 2%, 2 mm), photon beams measured with the BPW-34 diode centered at 10 $\times$ 10 cm^2 field size. The experimental data are plotted with the theoretical values predicted by the Eclipse treatment planning system based on the Monte Carlo code. Regardless of the photon energies, the experimental data and the Eclipse TPS calculations match better than 2%. In particular, the PDD profiles of 6 MV and 6 MVFFF the 100% percentage gamma passing rate (red line in Fig. 8 a, c) is 100% with 1% dose difference and 1 mm distance. For the 15 MV energy, the gamma passing rate is 29.4 % with an evaluation criteria 1% and 1 mm, while with a criteria of 2% and 2 mm the gamma passing rate is 94.1% (Fig. 8b).

The same analyses were performed for a commercial diode EDGE (Sunnuclear), and the results for 6 MV were 70.6% (gamma criteria 1%, 1 mm) and 94.1% (gamma criteria 2%, 2 mm). Energy of 6 FFF 100% (gamma criteria 1%, 1 mm), and 15 MV 76.5% (gamma criteria 1%, 1 mm) and 94.1% (gamma criteria 2%, 2 mm). Both diodes have a greater impact on gamma differences for the energy of 15 MV, not only in the buildup but also in depth. In a broader sense, an analysis of 2 mm and 2%, more than 90% of the points are approved for both.

4. Conclusions

The characterization of the BPW-34 diode thoroughly presented in this work endorses that it can be used for dosimetric measurements of photon beams from linear accelerators in radiotherapy services. The dosimeter proved very reproducible, presenting a coefficient of variation of 0.3% for 6 MV photons. The sensitivity results were compared with commercial diodes, and the BPW-34 showed greater sensitivity than most. The response as a function of the dose rate showed a maximum coefficient of variation of 0.25%, indicating that the detector can be used over a wide range of dose rates. The output field factor values and the percentage depth dose profiles agreed well with the Eclipse TPS calculations. It was also observed that the smaller the field size is, the greater the OFF variations, reaching 3.4% for a 1 $\times$ 1 cm^2 field size, similar to the results gathered with the commercially available EDGE diode. Such uncertainties, which can lead to inaccuracies in the dose planned for the patient, should be reduced by evaluating the OFF corrections factors, alike commercial diodes, following the TRS 483 recommendations. Investigations in this direction are ongoing.

Furthermore, the overall dosimetric performance of the BPW-34 device herein investigated, comparable to several commercially available diodes, showed that it could be a reliable and low-budget tool for quality assurance programs required in radiotherapy procedures.

CRediT authorship contribution statement

Iandra T. Silva: Investigation. **Karen Pieri:** Data curation. **Lucas D. Albino:** Investigation. **Thiago S. Fontana:** Data curation. **Matheus F. dos Santos:** Data curation. **Ernesto Roesler:** Resources. **Charles N.P. Oliveira:** Investigation. **Viviane K. Asfora:** Formal analysis. **Josemary A.C. Gonçalves:** Writing – review & editing, Writing – original draft, Investigation. **Helen J. Khoury:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Conceptualization. **Carmen C. Bueno:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization.

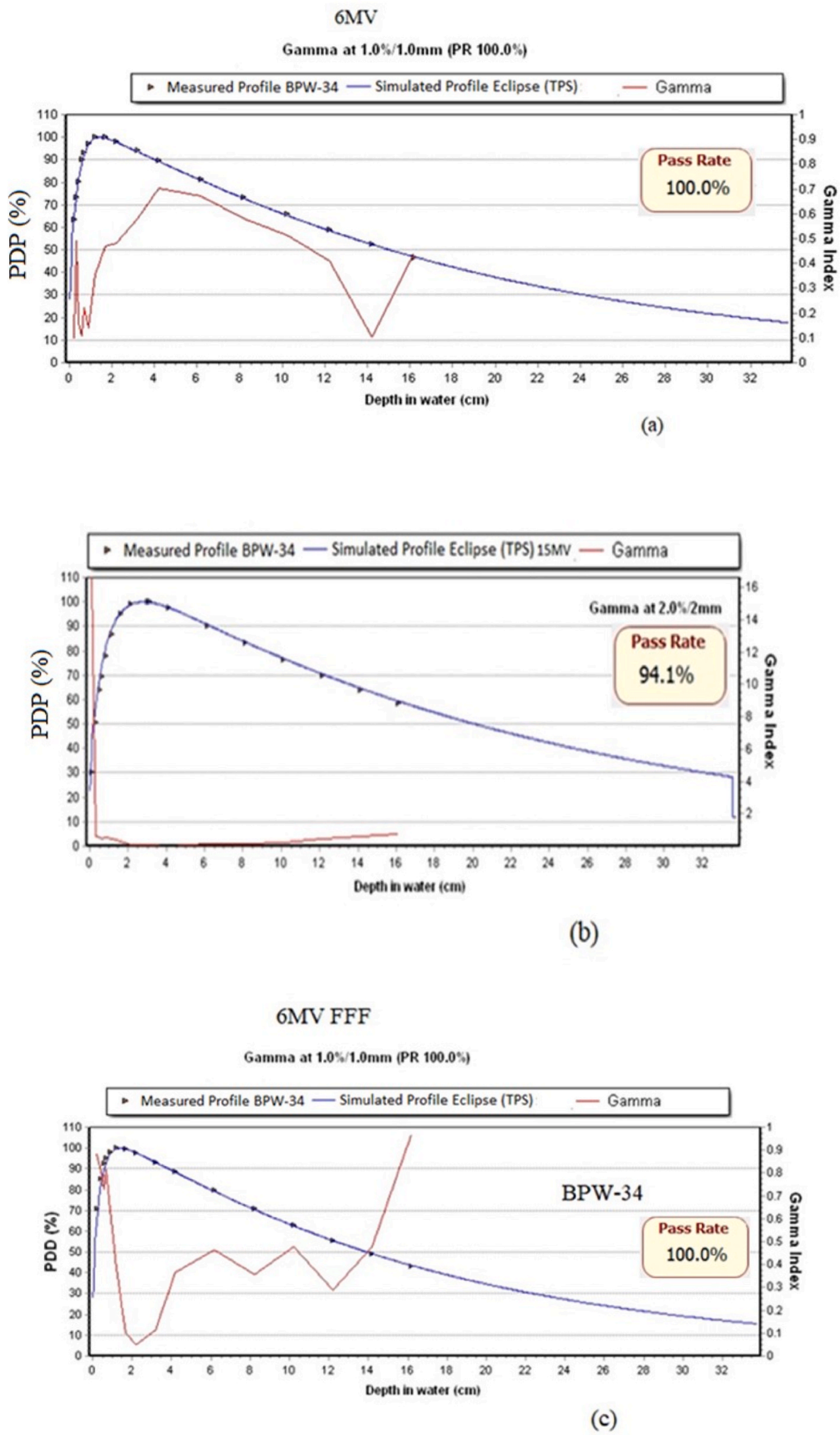

Fig. 8. Percentage depth dose (PDD) profiles of (a) 6 MV, (c) 6MVFFF, (1%, 1 mm) and (b) 15 MV (2%, 2 mm) photons gathered with the BPW-34 diode. The theoretical values from the Eclipse treatment planning system are shown for comparison.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

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