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Application of optically stimulated luminescence 'nanoDot' dosimeters for dose verification of VMAT treatment planning using an anthropomorphic stereotactic end-to-end verification phantom

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HIGHLIGHTS

- Landauer OSL InLight System applied for VMAT dosimetry.
- $CaSO_4$:Dy + Teflon pellets produced at IPEN as TL dosimeters for VMAT QA.
- Validation for both TL and OSL dosimetry using PTW PinPoint3D ion chamber.
- Landauer OSL InLight System as practical tool for clinical dosimetry.

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ABSTRACT

This paper aims to evaluate the performance of the commercial OSL Landauer InLight System to be applied in dosimetric measurements in a Volumetric Modulated Arc (VMAT) brain tumor planning treatment using a *Stereotactic End-To-End Verification Phantom Patient* (*STEEV*™ – CIRS), comparing its results with $CaSO_4$:Dy TLD pellets manufactured and marketed by the Laboratory of Dosimetric Materials/IPEN, PTW *PinPoint*™ ion chamber and Eclipse 10.0 planning system. The results of commercial InLight™ System using the nanoDot dosimeters showed good reproducibility and stability in both laboratory and clinical measurements. The experimental dose values obtained by all dosimetric techniques varied less than ±1.0% from prescribed by Eclipse 10.0. The intrinsic precision and uncertainty of the OSL reading device were found fair enough, providing good experimental results for VMAT dosimetry.

1. Introduction

The modulated arc therapy (VMAT) is the most advanced form of intensity modulated radiotherapy treatment (IMRT) and it is becoming an important external radiotherapy technique worldwide. The treatment is delivered with a single or multiple arc rotations of the linear accelerator gantry, during which the Multileaf collimator (MLCs) move dynamically while the dose rate and gantry speed vary continuously (Otto, 2008). Considering its complexity, beside a highly qualified and multidisciplinary staff for clinical routine, a quality assurance program must be established by evaluating, among other items, the patient dosimetry. The dosimetry aims to verify and validate the planning system prescribed dose and the radiation dose received by the patient in treatment. The main type of dosimeter used in modulated radiotherapy dose verification is ionization chambers, however, there are several other dosimeters that has been used in the checking of high-energy photon beams, among them, MOSFETs and diodes (Low et al., 2011).

Well-established in literature, luminescent materials using TL and OSL techniques have documented experiences in the field of clinical dosimetry, primarily performed using lithium fluoride (LiF:Mg,Ti), Calcium Sulfate ($CaSO_4$:Dy) TL dosimeters (Nunes and Campos, 2008; Bravim and Campos, 2009; Matsushima et al., 2012, 2014) and aluminum oxide (Al_2O_3:C) OSL dosimeters (Jursinic, 2007; Viamonte et al., 2008), proposing its use as alternative methods for external beam quality assurance.

The Dosimetric Materials Laboratory of the Instituto de Pesquisas Energéticas e Nucleares (IPEN-LMD) developed and have been producing $CaSO_4$:Dy + Tefflon sintered pellets on a commercial scale (Campos and Lima, 1986). The application of the

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$CaSO_4$:Dy in radiation therapy dosimetry is of great interest, given the ease of acquisition of dosimeters from IPEN and due to their characteristics of sensitivity and linearity response to radiation (Nunes and Campos, 2008).

The aluminum oxide has being proving good results as luminescent detector for photons and electrons as well as shown in literature (Akselrod et al., 2007; Yukihara and McKeever, 2008). In order to generalize the use of OSL dosimetry, Landauer Inc. (Landauer, Inc., Glenwood, IL) has developed a commercial system known as Inlight™ system (Perks et al., 2007). First developed for use in individual monitoring and radiation protection, this system has been tested for quality assurance dosimetry for diagnostic (Al-Senan and Hatab, 2011; Zhang et al., 2013), radiation protection for interventional radiology (Sanchez et al., 2014) and external radiation therapy (Jursinic, 2007; Viamonte et al., 2008) with good results. Commissioning of the system for use in radiation therapy has been proposed (Dunn et al., 2013) and VMAT dosimetry applications are also being investigated (Opp et al., 2013).

Thus, the main goal of this work is to evaluate the performance of the commercial 'Landauer InLight System' to be applied in dosimetric measurements in a Volumetric Modulated Arc (VMAT) brain tumor treatment using a Stereotactic End-To-End Verification Phantom (STEEV™ – CIRS), comparing its results with $CaSO_4$:Dy TLD pellets from LMD/IPEN, PTW PinPoint™ ion chamber and Eclipse 10.0 prescribed plan.

2. Material and methods

2.1. Dosimeters and readout systems

In this study, 35 $CaSO_4$:Dy + Tefflon pellets produced by IPEN were used. They are thin sintered pellets of $CaSO_4$:Dy pressed in a matrix of polytetrafluorethilene (PTFE) with dimensions of 6.0 mm in diameter and 0.8 mm in thickness, highly sensitive to photons to be used as TLD dosimeters (Fig. 1A) (Campos and Lima, 1986).

It was also used 25 nanoDot dosimeters, which are 5 mm diameter, 0.2 mm thick disk-shaped Al_2O_3:C, encased in a light-tight plastic with dimensions of 10 × 10 × 2 mm^3 (Fig. 1B). The samples were granted by SAPRA LANDAUER Serviços de Acessoria e Proteção Radiológica, representative of Landauer Inc. in Brazil.

For nanoDots readout, it was used the InLight System, from LMD/IPEN. The reading system consists of the microStar reader connected to a notebook for dose calculations by microStar software. It uses Light Emitting Diodes (LED) emitting light at a wavelength of 532 nm (green) as source of stimulation (Perks et al., 2007).

The TL responses of $CaSO_4$:Dy pellets were evaluated in a Harshaw 4500 TLD reader, in nitrogen atmosphere with a linear heating rate of 10 °C.s^{-1}. The reading cycles were performed within 30 s, with maximum temperature of 300 °C reached in each readout cycle (Campos and Lima, 1986; McKeever et al., 1995). They were programmed using a computer connected to the unit with WinRems software.

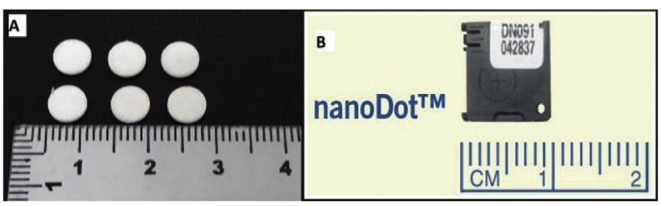

Fig. 1. TL and OSL dosimeters used. (A) $CaSO_4$:Dy + Teflon pellets produced at IPEN. (B) Landauer nanoDot dosimeters.

An waterproof ionizing chamber PTW, model PinPoint3D with sensitive volume of 0.015 cm^3 connected to an UNIDOS E electrometer was used as reference dosimeter, in order to help validating the obtained results and to be compared with Eclipse 10.0 planned treatment.

2.2. Bleaching and annealing treatments

Umisedo et al. (2010) documented that using blue wavelength for optical bleaching of A_2O_3:C OSLDs is efficient when the OSLDs are readout with green light stimulation. Thus, optical beaching of the OSL samples was performed using an Ourolux® 1.3 W of power lamp, composed of 30 blue LEDs. The sensitive Al_2O_3:C volume of the samples were exposed for ~12 h and, since the residual signal is dependent on the previous exposures, prior every further irradiations the 'background' signal was read for each dosimeter. The $CaSO_4$:Dy samples were thermally annealed in a Vulcan 3–550 PD furnace, at 300 °C for three hours (Campos and Lima, 1986; McKeever et al., 1995).

2.3. Irradiations

The InLight System's microStar reader, the nanoDot dosimeters and the $CaSO_4$:Dy TLD pellets were formerly tested at the IPEN to a standard reference response of 1.25 MeV energy ^{60}Co gamma ray irradiator (0.339 TBq ± 3.5% in September/1999) with kerma rate of 0.276 mGy/s (±2%). It was used a field size of 12.5 × 12.5 cm at 1.28 m of distance from the source. For clinical dosimetry measurements, both materials were calibrated using 6 MV photon beam from a linear accelerator VARIAN NOVALIS TX at Sírio-Libanês Hospital (HSL). The characterization measurements were carried out within depth of maximum dose.

2.4. Calibrations and performance tests

The $CaSO_4$:Dy pellets were tested and selected according to their sensitivity and repeatability better then ±5% to ^{60}Co. The pellets were annealed and irradiated in electronic equilibrium conditions (3 mm PMMA thickness plates) and absorbed dose of 25 mGy, read, and this process was repeated five times to define, through the mean read value, the sensitivity of the TL pellets. (Nunes and Campos, 2008).

The nanoDots used in this study have already come with their individual sensitivities factors labeled with accuracy of ±5%. This factor depends upon the amount of Al_2O_3:C in each sample (Yahnke, 2009). In order to confirm the "screening" of the dosimeters and ensure that the OSL responses are all similar, the same process of the $CaSO_4$:Dy pellets was performed.

To perform the clinical characterization of both types of dosimeters, they were separated into groups of 3 nanoDots and 4 $CaSO_4$:Dy, irradiated in a linear accelerator VARIAN NOVALIS TX at HSL with 6 MV photon beam using solid water SW phantom. Irradiations were carried out in depth of maximum dose (1.5 cm) with set up field of 10 × 10 cm^2 and source-skin distance (SSD) of 100 cm. To ensure adequate photon backscatter, 8 cm of solid water SW phantom was used under the dosimeters.

Dose-response curves were obtained for doses ranging 25 up to 300 cGy. This particular range was chosen by the linearity of response of both materials (Campos and Lima, 1986; Yukihara and McKeever, 2008), following the InLight calibration guide (Yahnke, 2009) and for its applicability to radiotherapy using conventional fractionation (1.8–2.0 Gy per fraction).

Fitting a linear curve to each dose-response, the calibration factors for both TL and OSL dosimeters, F_{cal}, are obtained and thus, the Lower Detection Limit of the dosimetric systems are calculated

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using Eq. (1)

$$LDL = \left(\overline{R_0} + 3 \cdot \sigma_{\overline{R_0}}\right) \cdot F_{cal} \quad (1)$$

where $\overline{R_0}$ is the mean value for the dosimeters readouts of non-irradiated dosimeters and $\sigma_{\overline{R_0}}$ is its corresponding standard deviation.

To evaluate the microStar performance and establish the intrinsic precision and uncertainty of the device, it was performed a $CV_{\%}$ test, using Eq. (2)

$$CV_{\%} = \left(\frac{\sigma_{R_{QA}}}{\overline{R_{QA}}}\right) \cdot 100 \quad (2)$$

where $\overline{R}_{QA}$ is the mean of 10 OSL repeated readouts of a QA dosimeter irradiated with 2 Gy and $\sigma_{R_{QA}}$ the standard deviation of the 10 readouts. For oncology measurements, this should be less than 2% (Yahnke, 2009). To ensure the low-level, non-dosimetric electron traps are stable, the $CaSO_4$:Dy and Al_2O_3:C nanoDot readout were performed after 24 h and at 30 min, respectively (Jursinic, 2007; Yahnke, 2009; Dunn et al., 2013; McKeever et al., 1995; Nunes and Campos, 2008).

2.5. VMAT treatment planning and delivering

A Stereotactic End-to-End Verification 'STEEV' phantom (CIRS) was used to simulate a VMAT brain tumor treatment. This phantom is tissue equivalent with removable skull vertex that provides access to a rectangular brain cavity that receives interchangeable quality assurance (QA) and dosimetry inserts. This makes possible to simulate treatments throughout the region of head, brain and neck with greater anatomical rigidity and reliability.

The tumor volume to be treated was determined by two of the QA inserts, which has identical circular tissue-equivalent tumor mass into its composition: one of them adapted for a PinPoint3D ion chamber usage; and the other with perfectly adjusted geometry for fitting tight into the phantom, with no adaptable gap for dosimeters. So, with the need to accommodate the dosimeters into the tumor volume to be treated, small molds of dental wax were developed to fix the dosimeters in the central position of the insert. Fig. 2A and B show the molds for nanoDots and $CaSO_4$:Dy respectively. Fig. 2C show 'STEEV' phantom patient with opened skull and QA inserts to be fitted together.

After computer tomography scan, a VMAT brain tumor treatment with eyeballs, chiasmus and brainstem protection was planned using Varian Eclipse 10.0 software, Varian RapidArc technology and VARIAN AAA calculation algorithm (Fig. 3). Considering the incentive to assess the dose within a small volume, it was used calculation grid of 1 mm.

The treatment was delivered using nanoDots and $CaSO_4$:Dy dosimeters separately (Fig. 4). This process was repeated five times to improve statistics, and by the fact that it was only possible to use one dosimeter at a time. The irradiations were carried out in order to verify the performance of the Al_2O_3:C nanoDot and $CaSO_4$:Dy + Tefflon dosimeters and their agreement with VMAT Eclipse 10.0 planed treatment using the PinPoint3D ion chamber as tool for results validation.

Each presented value of absorbed dose is the average of the five dosimeters measurements, and the error bars present the standard deviation of the mean. All the calculations were done with the Microsoft Excel 2016 software, the calibration curves were plotted, without showing the error bars when the experimental errors are smaller than the data points, using OriginPro 8.1, that also provided

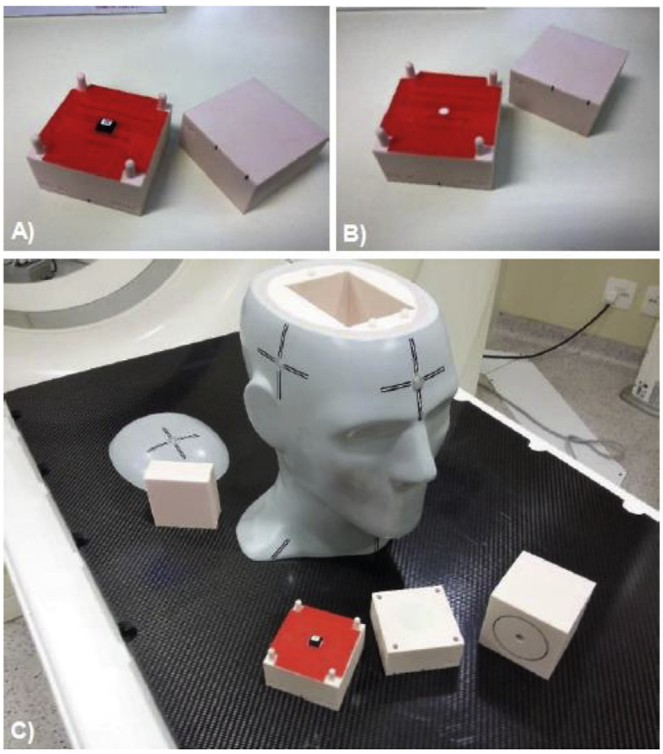

Fig. 2. 'STEEV' phantom patient and QA inserts used. (A) mold of dental wax and nanoDot centered into the target volume. (B) CaSO4:Dy TL dosimeter also centered into the target volume with specific dental wax mold. (C) 'STEEV' phantom patient.

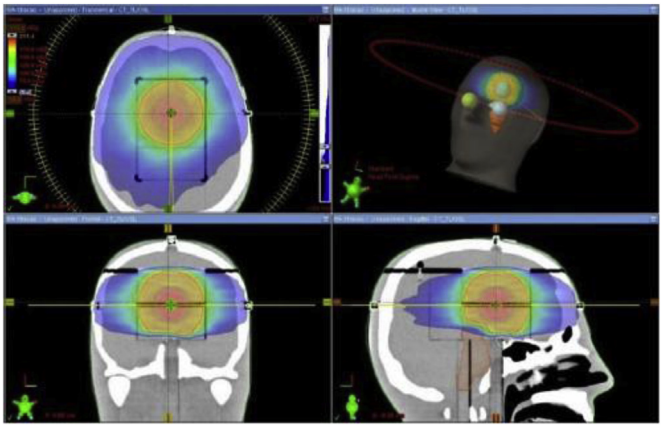

Fig. 3. 'STEEV' phantom patient's dose distribution planned with Eclipse 10.0.

the fit curve and its parameters. Chi-square of the calibration curves were calculated using webROOT software by High Energy Physics and Instrumentation Center – HEPIC/USP.

Among the planning systems available in radiation therapy, it is common to find the dose values showed in centigray (cGy), since the dosimetric uncertainty might be up in hundredths of cGy. So, for comparative purposes, it was chosen to express the experimental doses in cGy.

3. Results

3.1. Performance tests

The repeatability for both nanoDot and $CaSO_4$:Dy dosimeters is

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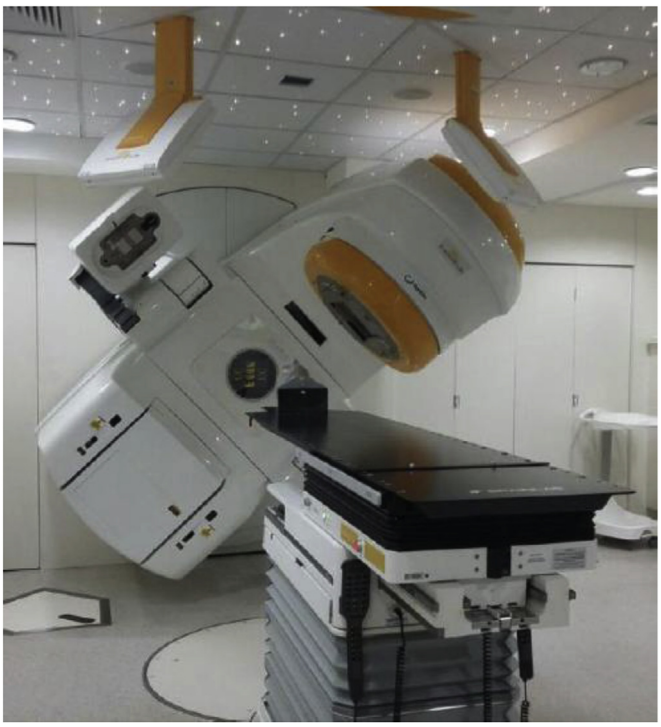

Fig. 4. 'STEEV' phantom positioned over the couch of treatment in the VARIAN NOVALIS TX linear accelerator of HSL.

better than ±4.0%. The experimental LDL is 4.8 ± 0.1 μGy for nanoDots, and 28.7 ± 0.4 μGy for $CaSO_4$:Dy dosimeters respectively and they agree with radiation therapy application. The InLight microStar reader presented stable results, with CV of ~1.5%, and prior every irradiation, dosimeters presented 'background' residual signal of 118 ± 12 counts.

3.2. Clinical characterization

The experimental calibration factors were 606.48 ± 3.02 counts/cGy for the nanoDots and 1409.6 ± 19 nC/cGy for $CaSO_4$:Dy pellets. The dose-response curves for both dosimetric materials to linear accelerator VARIAN NOVALIS TX for absorbed doses from 25 up to 300 cGy are presented in Fig. 5. It can be observed the expected linear behavior of response of both materials. It is expected that chi squared values are close to the degree of freedom of the system if the fitting is satisfactory. With our experimental data, the values found were 1.69 and 1.92 for nanoDot and $CaSO_4$:Dy respectively, so the fitted curves are fine.

3.3. 'STEEV' patient dosimetry

Using the calibration factors obtained by the slope of both linear fitted curves, the maximum, minimum and mean absorbed doses

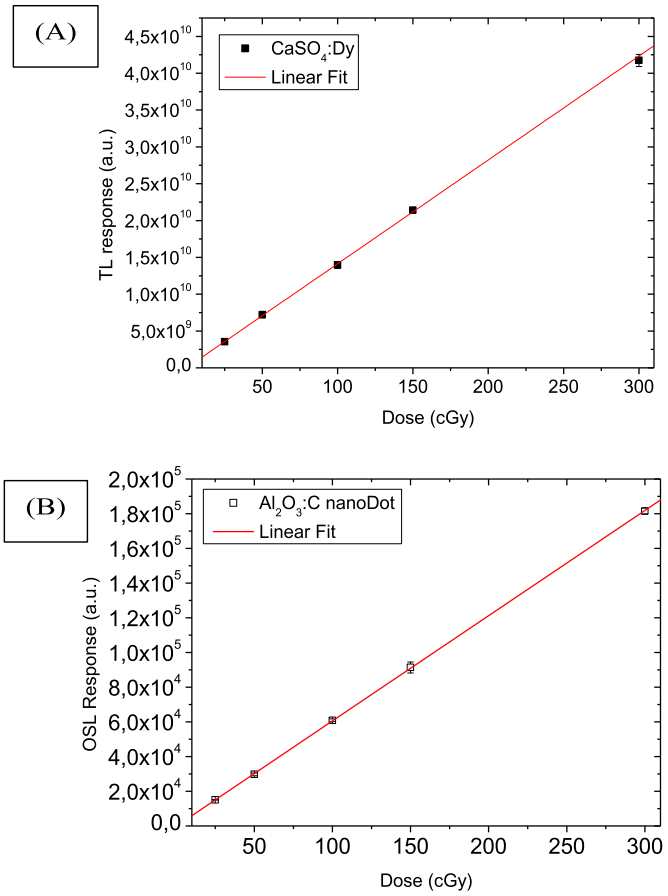

Fig. 5. Dose-response curves obtained with $CaSO_4$:Dy (A) and Al_2O_3:C nanoDots (B) for doses from 25 up to 300 cGy.

evaluated by Al_2O_3:C nanoDots and $CaSO_4$:Dy dosimeters were calculated and the results are shown in Table 1, along with PTW PinPoint3D ion chamber dosimetry and Eclipse 10.0 prescribed doses. The variation of maximum and minimum doses from Eclipse planning system show the homogeneity of planned doses into dosimeters volume (~0,1 cm^3). The minimum and maximum values measured with the dosimeters show the experimental variation in between the different measurements.

The agreement between planning and the measured doses was evaluated by the deviations, $Dev_{(\%)}$, between the mean planed and measured doses with the different dosimeters, using Eq. (3)

$$Dev_{(\%)} = \left(\frac{Me - Mp}{Mp}\right) \cdot 100 \quad (3)$$

where *Me* is the mean experimental absorbed doses, and *Mp* is the mean dose given by Eclipse 10.0.

Fig. 6 shows the visual representation of the planning

Table 1
Mean, Maximum and Minimum doses given by VMAT planning system and obtained with the nanoDots, $CaSO_4$:Dy and PTW PinPoint3D ion chamber within dosimeters target volume.

	Absorbed Doses (cGy)			Max/Min (%)	Deviation (%)[a]
	Minimal Dose	Maximal Dose	Mean Dose		
Eclipse 10.0 Planned	202.4	205.8	203.7 ± 1.7	−1.7	–
nanoDots	201.6	205.5	204.2 ± 0.7	−1.9	+0.2
$CaSO_4$:Dy	198.6	204.9	202.0 ± 1.3	−3.2	−0.8
PTW PinPoint3D	202.2	203.9	203.0 ± 0.3	−0.8	−0.3

[a] Deviation between each mean dose measured and the mean dose planned by Eclipse 10.0.

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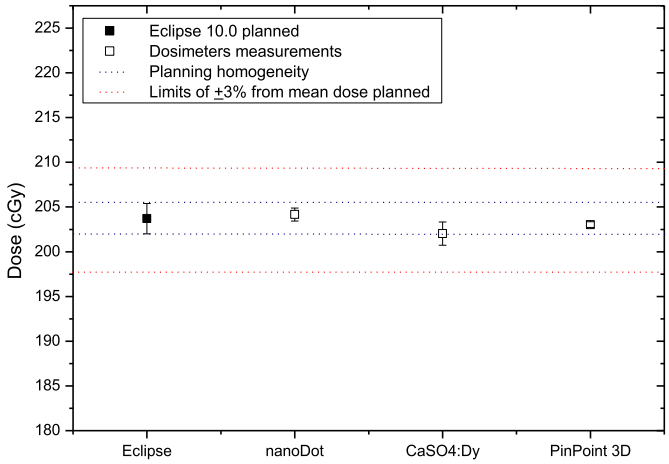

Fig. 6. Planning homogeneity and the agreement between the absorbed doses obtained with dosimeters, ion chamber and Eclipse 10.0.

homogeneity and the agreement with the experimental results. It can be noticed that the nanoDot and PinPoint3D measurements are fitted within planned treatment homogeneity and, despite a larger variation of $CaSO_4$:Dy measurements, all obtained values vary less than ±3.0% from the mean dose planned.

The highest dose fluctuations are observed with $CaSO_4$:Dy, evidenced in the evaluation of the max/min ratio in Table 1, that can be explained by the repeatability of the pellets varying by ± 4.0%.

The nanoDots, with the individual screening correction factors given by Landauer, along with an intrinsic uncertainty of ~1.5% from the microStar reader, produce very exact dose results. The electronics and calibration of the PinPoint3D ion chamber, as expected, clearly generates precise results as well, helping to validate all measurements.

4. Discussion and conclusions

Previous studies have shown that changes in sensitivity depend on accumulated doses, time and wavelength of bleaching of the OSL dosimeters. Accumulated doses approximately above 10–20 Gy was found to induce sensitivity changes (Yukihara and Mckeever, 2008; Jursinic, 2010; Omotayo Azeez et al., 2012; Opp et al., 2013). In our experiments, the control of the effectiveness of the optical bleaching was obtained by means of the "background" readings of each OSLD before use, soon after the exposure to the blue LEDs. Only three nanoDots received accumulated doses greater than 3 Gy (upper value chosen for the calibration of the reader, plus performance test irradiations). Their 'blank' background readings remained stable, as reported in section 3.1, and sensitivity change was negligible.

The findings of this work indicate that the commercial InLight System using the nanoDot dosimeters produce good reproducibility and stability in both laboratory and clinical measurements. The intrinsic precision and uncertainty of the device were found sufficient for dosimetric measurements in VMAT plans.

The $CaSO_4$:Dy + Teflon pellets, as predicted, presented good performance as well, and all results agreed with ion chamber data and Eclipse 10.0 prescribed doses. All results were within ±3.0%, so the repeatability of TL and OSL was within acceptable limits for radiotherapy purposes.

Due to its versatility, the InLigh System can be applied as an alternative and practical tool for dose verification in VMAT treatment plans and met the performance requirements of ICRU Report 83 (2010)and AAPM's TG-142 (2009).

Acknowledgments

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