Al₂O₃:C and Al₂O₃:C,Mg optically stimulated luminescence 2D dosimetry applied to magnetic resonance guided radiotherapy

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**ABSTRACT**

The objective of this work is to demonstrate the potential application of Al₂O₃:C and Al₂O₃:C,Mg optically stimulated luminescence (OSL) films for 2D dosimetry in magnetic resonance guided radiotherapy (MRgRT), a modality which combines two dosimetric challenges: small field dosimetry and dosimetry in the presence of a magnetic field. To achieve that, prototype Al₂O₃:C and Al₂O₃:C,Mg OSL films produced by Landauer (Glenswood, IL, USA) were characterized using a MRIdian system (ViewRay Inc., Mountain View, California, USA). The system was initially equipped with three 60Co heads on a ring gantry combined with a 0.35 T split-magnet MRI system and later upgraded with a 6 MV flattening Filter-Free (FFF) linear accelerator, with a fixed dose rate of 600 MU/min. The dosimetric properties of the film material (Al₂O₃:C) in the magnetic field were first tested by irradiating samples of 7 mm in diameter read using a Risø TL/OSL automated reader for high precision. OSL films (Al₂O₃:C and Al₂O₃:C,Mg) were then tested at different doses and for two different intensity modulated radiation therapy (IMRT) treatment plans, for which the gamma analysis was performed using the 2D dose information obtained by readout of the films using a laser-scanning OSL reader. The results using the “point-dosimeter” samples showed deviations <4% with the delivered dose and variations within the same package of <4% (standard deviation of the data). The gamma analysis for IMRT plans showed pass rates >95% with a 3% - 3 mm criteria (>84% with a 2% - 2 mm criteria), with the failure typically happening in the edges of the film, not in the central high dose region. The results did not show any clear influence of the magnetic field and demonstrate the feasibility of Al₂O₃:C and Al₂O₃:C,Mg OSL dosimeters for 2D dosimetry in MRgRT.

1. Introduction

Recent developments towards real-time image guided radiotherapy hybrid devices have led to the combination of a magnetic resonance imaging (MRI) scanner with a radiotherapy unit, such as a linear accelerator or 60Co sources (Fallone et al., 2009; Jaffray et al., 2010, 2014; Lagendijk et al., 2014; Mutic and Dempsey, 2014). Such systems provide real-time imaging during the patient treatment, reducing uncertainties in the patient positioning and target localization and potentially improving the precision of the therapy.

Nevertheless, the Lorentz force alters the trajectory of the secondary electrons in the air cavities, which affects the detector response of ionization chambers according to the magnetic field strength and the orientation of the chamber (Meijssing et al., 2009; Reynolds et al., 2013; Smit et al., 2013; O’Brien et al., 2017). Other solid-state detectors such as diamond detectors, plastic scintillators and radiochromic films (Gafchromic EBT2 and EBT3, Ashland Inc.) are also affected by the magnetic field (Stefanowicz et al., 2013; Reynolds et al., 2014; Reynoso et al., 2016; Casumano et al., 2018; Delfs et al., 2018; O’Brien et al., 2018).

Luminescence detectors are now well accepted in medical dosimetry (Kry et al., 2020) and considered promising candidates for dosimetry in magnetic field (Jelen and Begg, 2019). Thermoluminescence detectors (TLDs) were found to show <1% field dependence up to 1.5 T transverse field (Wang et al., 2016; Wen et al., 2016; Steimann et al., 2019). Spindeldreier et al. (2017) observed a relatively small decrease in response of Al₂O₃ optically stimulated luminescence detectors (OSLDs) with increasing magnetic field (~1.3%/T) and no angular dependence. In addition, various luminescence techniques and materials have been...
recently investigated for potential 2D dosimetry applications in medicine (Li et al., 2014; Crijns et al., 2017; Souza et al., 2017; Nascimento et al., 2019; Sądel et al., 2020a, 2020b).

Al₂O₃:C are commercially available TL and OSL dosimeters with high sensitivity to radiation (Akselrod and Kortov, 1990), linear dose response (Jursinic, 2007; Viamonte et al., 2008; Reft, 2009), wide dynamic dose range (Akselrod and McKeever, 1999), potential dosimetric precision of <1% (Yukihara et al., 2005), minimal dark fading (Viamonte et al., 2008), low energy dependence of ±1% in MV X-ray beams (Viamonte et al., 2008), dose rate independent (Jursinic, 2007), and small angular dependence for MV X-ray beam (Jursinic, 2007). A review on the OSL technique and the application of Al₂O₃:C dosimeters in medicine can be found in Yukihara and McKeever (2008) and in a recent report of American Association of Physicists in Medicine Task Group 191 (Kry et al., 2020). In contrast to ionization chambers, the OSL detectors themselves (without casing or holders) do not have air cavities and are expected not to be influenced by magnetic fields.

Until recently, however, OSLDs were limited to point dosimetry. The slow luminescence of the F-center emission (35 ms lifetime), the main luminescence center in this material, prevented its use in 2D dosimetry using laser-scanning techniques, the imaging modality used in computed radiography. This situation changed with the development of a correction algorithm for Al₂O₃ films (Yukihara and Ahmed, 2015), which led to the development of laser-scanning 2D dosimetry based on Al₂O₃:C or Al₂O₃:C,Mg OSL films (Ahmed et al., 2014, 2017). Initial tests with 6 MV X-ray beams using Al₂O₃ films show that the films have low background (~mGy), linear response, wide dynamic range (4–5 orders), good spatial resolution (~1 mm), and potential dose uncertainty within 2% (Ahmed et al., 2014). An additional advantage of OSL films with respect to radiochromic films is their potential re-usability, since an inherent property of the OSL is that it can be bleached by light exposure (bleaching); e.g. see Crijns et al. (2017).

The objective of this work is to evaluate the performance of newly developed Al₂O₃:C and Al₂O₃:C,Mg OSL films for application in 2D dosimetry in the presence of a 0.35 T magnetic field. To achieve that, a MRidian system (ViewRay Inc., Mountain View, California, USA) was used to investigate the response of OSL films samples of 7 mm in diameter, read using an automated Risø OSL reader (DTU Nutech, Denmark) for high precision, and the response of OSL films (5.0 cm × 5.0 cm) read using a laser-scanning OSL reader. IMRT plans were also...
delivered to OSL films (10.0 cm × 10.0 cm) and the measured dose distributions were compared with those calculated using a dedicated treatment planning system (TPS) and the gamma analysis (Low et al., 1998; Low and Dempsey, 2003). The dosimetric properties of Al₂O₃:C are well-established – see Kry et al. (2020) and references therein – and the 2D dosimetry capabilities of the Al₂O₃ films were already reported (Ahmed et al., 2016b, 2017). Therefore, the present work is concerned primarily with possible effects of the presence of the magnetic field on the results.

2. Materials and methods

2.1. Detectors and readout

The Al₂O₃:C OSLD films (Lot. # 31218Y2N) and Al₂O₃:C,Mg OSLD films (Lot. # 41128Y2N) consist of a (47 ± 3) μm thick layer of Al₂O₃ powder mixed with binder and deposited on a 75 μm thick polyester substrate. The powder used in the Al₂O₃ films is made of the same material used in Luxel™ and InLight™ dosimetry systems (Landauer, Glenwood, IL, USA), but produced using material ground to smaller grain size (<15 μm median) (Ahmed et al., 2016b).

For tests requiring higher precision, OSL film samples of ~7 mm diameter were prepared from the same Al₂O₃:C OSLD films (Lot. # 31218Y2N) by punching out small round pieces. The detectors were packaged (five detectors per package) with black electric tape to protect them from light after irradiation, using a paper to protect the detectors from the tape glue. The small OSL film samples were read using a Riso TL/OSL-DA-20 reader (DTU Nutech, Denmark), which can achieve precision <1% per readout through automatic individual calibration of the detectors (Yukihara et al., 2005), but no 2D information is obtained. The reader is equipped with a 1.48 GBq ⁹⁰Sr/⁹⁰Sr beta source. The samples were stimulated with green LEDs (broad band centered at 525 nm, irradiance of ~40 mW/cm² at the sample position) and the light was detected using an ET Enterprises PMD9107Q-AP-TTL photomultiplier tube (PMT). Hoya U-340 filters (Hoya Corporation, 5 mm thickness) and a neutral density filter (Edmund Optics UV/VIS ND 1.0 OD, serial number EO 47207) were used in front of the PMT. The reader is equipped with a software-controlled Detection and Stimulation Head (DASH). The reader is also equipped with a Photon Timer attachment (Time-Correlated Single Photon Counter board, PicoQuant TimeHarp 260) for lifetime and time-resolved measurements. To avoid detection of the UV emission band of Al₂O₃:C, the samples were measured using the pulsed OSL (POS) mode, the LED being pulsed for 1 ms every 2 ms and the OSL being detected only when the LED is off. The samples were stimulated for 240 s and the total counts (minus background) were used as the OSL signal.

For the readout of the “point detectors”, the high-precision methodology described by Yukihara et al. (2005) was used. After the first readout to obtain the signal S, the detectors were irradiated with the Riso beta source for 300 s and read again to obtain a reference signal S₀. The ratio S/S₀ was then plotted against the beta irradiation time to obtain an “internal calibration” curve. In this procedure, the OSL signal is converted using the “internal calibration” into the beta irradiation time required to produce a signal of the same intensity. Using detectors irradiated with a known dose, the dose rate of the beta source can be obtained, from which the dose for detectors irradiated with an unknown dose can be determined. This procedure has the advantage of eliminating any variation due to detectors sensitivity and mass, enabling a precision <1% per detector in a convenient way (Yukihara et al., 2005).

For 2D dose measurements, the OSLD films were cut into 5.0 cm × 5.0 cm or 10.0 cm × 10.0 cm pieces and bleached using fluorescent lamps filtered with a Schott GG-495 filter (Schott AG). The films were then packaged in light absorbing adhesive flock papers, as described in Section 2.1.
2.2. Irradiations

The irradiations in magnetic field were performed using a MRIdian system at Fondazione Policlinico Universitario Agostino Gemelli (Rome, Italy). The system was initially equipped with three $^{60}$Co heads on a ring gantry combined with a 0.35 T split-magnet MRI system (Mucic and Dempsey, 2014) and was later upgraded with a 6 MV Flattening Filter-Free (FFF) linac with a fixed dose rate of 600 monitoring units (MU) per minute replacing the $^{60}$Co sources. In this system the magnetic field force lines are perpendicular to the radiation beam axis. Although the photon spectra of the $^{60}$Co and 6 MV FFF linac are different, here only relative results are presented and, therefore, this should not affect the results. A conventional LINAC (True Beam Edge, 6 MV FFF) was also used for additional tests.

The irradiations were carried out placing the detectors in two setups (Fig. 2). In Setup A (Fig. 2a), the detectors (packages containing “point detectors” or films) were placed in between 30.0 cm × 30.0 cm Solid Water (Solid Water, Gamex RMI, Iddlehton, WI 53562, USA) slabs at a depth of 1.5 cm with 10.0 cm material for backscattering and irradiated at a source-to-surface distance (SSD) = 85.0 cm, source-to-axis distance (SAD) = 90.0 cm, field size 9.96 cm, and 600 MU/min. Setup A was also positioned rotated ±90° with the gantry rotated accordingly to maintain the irradiation direction with respect to the detector orientation, therefore changing only the orientation of the detectors with respect to the magnetic field lines. Since cylindrical symmetry of the equipment is assumed, the irradiations should be identical.

In setup B (Fig. 2b), packages containing points detectors were placed in a cylindrical phantom of 7.0 cm diameter by 25.5 cm length. The cylinder itself was placed in a 5.0 mm thick PMMA shell to allow the rotation of the cylinder. The detectors were placed at different angles with respect to the vertical (0°), the gantry being rotated accordingly so that the irradiation is always perpendicular to the dosimeter plane, as shown in Fig. 2. The beam field size was large enough to guarantee a dose uniformity better than 1% within the dosimeter package. Again, the objective here was to maintain the orientation of the irradiation with respect to the dosimeters and only change the dosimeter orientation with respect to the magnetic field lines.

Irradiations with two IMRT plans were also performed using a setup similar to Setup A, but with the OSL films positioned at a depth of 5.0 cm and with 10.0 cm of material for backscattering.
2.3. Gamma analysis

The gamma analysis algorithm used here is the same described in Low et al. (1998). The spatial resolution of the calculated image was 1.25 mm and was interpolated to 1.0 mm. In the case of OSL images the image was binned into 4 pixels × 4 pixels to convert the pixel size into 1.0 mm × 1.0 mm. A 5 pixels × 5 pixel Wiener filter (Gibbs, 2011) implemented in Mathematica (Wolfram Research) was applied to further smooth the image. The points with dose <10% of the maximum dose were excluded from the analysis.

Fig. 7. (a) Images of the IMRT plan I and the resulting OSL images for (b) Al₂O₃:C and (c) Al₂O₃:C,Mg films irradiated on a phantom (Fig. 2a) at 5.0 cm.
3. Results and discussion

3.1. Tests with “point” detectors

The linearity of the Al₂O₃:C film response in the presence of magnetic field was checked by irradiating packages containing the “point detector” samples of the OSLD films with six different doses from 0.5 Gy to 10 (5 detectors for each dose) using the MRIdian linac system with a static magnetic field of 0.35 T using a field size of 9.96 cm × 9.96 cm at 1.5 cm depth. The samples were then read out using the Risø reader as described in Section 2.1.

Fig. 3 shows a plot of the OSL response, which is the OSL signal converted into the Risø beta source irradiation time (s) required to obtain a signal of the same intensity, as a function of the dose delivered by the MRIdian system. The response of the film material was observed to be linear and the dose rate of the Risø source was then estimated to be 48.5 mGy/s. Although the dose response of Al₂O₃:C is known to become supralinear after a few grays, this is not seen here because the use of the S/S_R method, possible with the Risø reader, eliminates this effect (Yukihara et al., 2005). For the film, this will not be possible, and the OSL signal will be expressed in PMT counts.

The standard deviation of the data for the five detectors was in average 2.5%, indicating the expected uncertainty for each detector due to the readout procedure only. This value is larger than the 0.7% previously reported for 50 detectors irradiated with a Varian linear accelerator (Yukihara et al., 2005). Identical irradiations were repeated in parallel using a conventional LINAC and the ViewRay LINAC (see Section 2.2), but the results were identical, with standard deviation within the packages of 2.4–2.6% in average. This suggests that the increased standard deviation may be related to other influencing factors not identified (sample, packaging, irradiation conditions) and not the influence of magnetic field. The reproducibility of S/S_R ratios obtained for the internal calibration (see Section 2.1), when all detectors are irradiated using only the Risø beta source, was <0.7%, showing that the reader itself does not seem to be the cause for the increased uncertainty.

Measurements were made with OSLD packages placed at 0.5 cm and at 1.5 cm to determine the feasibility of using OSLDs as in-vivo dosimeters. The irradiations were performed delivering a dose of 2.0 Gy at 1.5 cm. The results were (1.79 ± 0.03) Gy at 0° and (2.00 ± 0.03) Gy at 90°. The results show a good agreement with the delivered dose and indicates no dependence with the different positioning of the OSLDs with respect to the field lines. The standard deviation of the mean value based on the 5 detectors; the standard deviation of the data were 4.0% and 3.0% respectively. This result shows the potential of using the OSLDs as in-vivo dosimeters in MRgRT.

The irradiation with OSLD packages at 1.5 cm was repeated once in setup A (Fig. 2) and then rotating setup A and the gantry to ±90°, keeping the delivered dose 2.0 Gy. The results obtained were (1.94 ± 0.02) Gy at 0°, (2.00 ± 0.03) Gy at +90° and (2.01 ± 0.03) Gy at −90°. The data at zero degrees (~3.1% discrepancy with delivered dose) provides an idea of the reproducibility of the irradiation and detector positioning. Nevertheless, the data at ±90° show good agreement with the delivered dose and indicates no dependence with the different positioning of the OSLDs with respect to the field lines. The standard deviation of the mean value based on the 5 detectors; the standard deviation of the data were 4.0% and 3.0% respectively. This result shows the potential of using the OSLDs as in-vivo dosimeters in MRgRT.

Fig. 8. Gamma analysis results for the IMRT plan I (data from Fig. 7) for (a) Al₂O₃:C and (b) Al₂O₃:C,Mg films obtained using 3% - 3 mm criteria. Red pixel indicates pixel with points failing the gamma criteria. Comparison of central dose profiles of images of IMRT plan with Al₂O₃:C and Al₂O₃:C,Mg films the (c) x-axis and (d) y-axis. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
deviation of the data was in average 3.2%.

A final test was performed irradiating the OSLD packages in the center of a cylindrical phantom (Fig. 2b). In this setup, different irradiations were performed positioning the cylindrical phantom and the gantry at angles of $0^\circ$, $45^\circ$, $90^\circ$, $270^\circ$, $315^\circ$ from the vertical ($0^\circ$), keeping the irradiation perpendicular to the detector plane, as shown in Fig. 2b. The plan was calculated to deliver a dose of 2 Gy at the detector plane.

Fig. 4 shows the response of the OSLDs as a function of the phantom/gantry angle. In this experiment the measured dose was 2% higher than the given dose (2.0 Gy) at $0^\circ$, but 3% higher than the give dose at $90^\circ$ and ~4% at $270^\circ$. These discrepancies may be due to the setup geometry. The standard deviation of the data was in average 3.1%, not higher than the irradiations in setup A, indicating a relatively uniform irradiation field. Although this discrepancy cannot be explained at the moment, we can see in Fig. 4 that the difference with respect to the mean measured dose is only ±2%.

3.2. Tests with OSLD films

The dose response for Al$_2$O$_3$:C and Al$_2$O$_3$:C,Mg films were determined using the MRgRT system with $^{60}$Co as the radiation source. The 5.0 cm × 5.0 cm OSLD films were irradiated in a phantom (Fig. 2a) with 10.5 cm × 10.5 cm flat field at a depth of 5.0 cm for doses from 0.1 Gy to 10 Gy. Fig. 5 shows an image of the Al$_2$O$_3$:C film irradiated with a total delivered dose of 2.0 Gy. The low dose at the edge of the films indicates the limit of the OSL films themselves.

To compare the image uniformity for two films at different doses, we calculated the signal profiles (average of 1.0 cm) at the center of the image in both x and y axes. The dose response curve was calculated using the average signal over a central region of interest (ROI) 2.0 cm × 2.0 cm (80 pixels × 80 pixels). Fig. 6a and b show two overlapping signal profiles for each dose calculated in perpendicular directions (x and y directions). As can be seen the x and y-profiles overlap at any dose level. These results demonstrate no influence of the magnetic field in the determination of dose homogeneity of the field.

Fig. 6c shows the OSLD film response versus delivered dose for both Al$_2$O$_3$:C and Al$_2$O$_3$:C,Mg films. The dose-signal relationship was fitted with the function $D = a(1 - e^{-bS})$. This function is not physical in the sense that it does not saturate with dose, but similar functions were shown to describe the supralinearity of the OSL of Al$_2$O$_3$:C in the limited dose range investigated here (Ahmed et al., 2016b). The Al$_2$O$_3$:C film has a response ~40% higher than the Al$_2$O$_3$:C,Mg film, but Al$_2$O$_3$:C,Mg films show a better (~50%) signal-to-noise ratio (SNR = $S/\sigma$). This is due to the smaller correction required for pixel bleeding for the Al$_2$O$_3$:C,Mg film in comparison with the Al$_2$O$_3$:C film. The OSLD films also show the onset of supralinearity for doses above a few grays, as it is known for Al$_2$O$_3$:C (Kry et al., 2020). These aspects were already reported before
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Ahmed et al., 2016b) and here we only note that the magnetic field did not influence the results.

Al₂O₃: C and Al₂O₃:CMg OSLD films (10.0 cm × 10.0 cm) were irradiated on a phantom (Fig. 2a) with two different treatment plans using the MRIdian system at a depth of 5.0 cm. The films were read out using the laser-scanning 2D dosimetry reader and the dose was calculated for each pixel using the calibration curve from Fig. 6c.

Fig. 7 shows the TPS dose map of the IMRT plan I (Fig. 7a) and the doses measured using the Al₂O₃: C films (Fig. 7b) and the Al₂O₃:CMg films (Fig. 7c). The plan shown in Fig. 7a was generated by nine step-and-shoot IMRT fields, with an equal angular distance of 40°, with a total of 72 modulated segments. The dose distribution was normalized to deliver 4 Gy to 50% of the STAR-shaped target. The dose calculation was performed by a Monte Carlo algorithm (ViewRay Inc., Mountain View, California, USA) with dose grid resolution of 0.1 cm. The OSL 2D dose map shows a good agreement with the TPS.

Fig. 8 shows the gamma analysis for a criteria of 3% and 3 mm for both Al₂O₃: C (Fig. 8a) and Al₂O₃:CMg films (Fig. 8b). The high dose regions pass the gamma analysis, whereas the region that fails the criteria are low dose regions with high dose gradient. Fig. 8 also shows the dose profiles at the center of the Al₂O₃: C (Fig. 8c) and Al₂O₃:CMg (Fig. 8d) films and IMRT plans. The OSL dose profiles from both materials agree well with each other and with the TPS.

Table 1 summarizes the gamma analysis for the two treatment plans, for both Al₂O₃: C and Al₂O₃: CMg films.

![Gamma analysis results for the IMRT plan II (data from Fig. 9) for (a) Al₂O₃: C and (b) Al₂O₃:CMg films obtained using 3% - 3 mm criteria. Red pixel indicates pixel with points failing the gamma criteria. Comparison of central dose profiles of images of IMRT plan with Al₂O₃: C and Al₂O₃: CMg films for the (c) x-axis and (d) y-axis. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.]

(Protocols for treatment planning and dosimetry are provided in the Supporting Information.)

Table 1
Summary of gamma analysis for the IMRT Plans I and II using Al₂O₃: C and Al₂O₃:CMg films.

<table>
<thead>
<tr>
<th>Material</th>
<th>Plan I</th>
<th>Plan II</th>
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<tbody>
<tr>
<td></td>
<td>3% - 3 mm</td>
<td>2% - 2 mm</td>
</tr>
<tr>
<td>Al₂O₃: C</td>
<td>98%</td>
<td>95%</td>
</tr>
<tr>
<td>Al₂O₃:CMg</td>
<td>98%</td>
<td>95%</td>
</tr>
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Fig. 9 shows similar results for the IMRT plan II. The plan shown in Fig. 9a was generated by three 3.15 × 3.15 cm² fields, with a gantry angle of 340°, 0° and 20°. The dose calculation was performed by a Monte Carlo algorithm (ViewRay Inc., Mountain View, California, USA) with dose grid resolution of 0.1 cm. Fig. 10 shows again the gamma analysis for a criteria of 3% and 3 mm and the dose profiles for both Al₂O₃: C and Al₂O₃:CMg films. The results are essentially identical to those obtained for the IMRT Plan I.

Table 1 summarizes the gamma analysis for the two treatment plans, for both Al₂O₃: C and Al₂O₃:CMg films. Additional results are included for a 2% - 2 mm pass criteria. The results show that a gamma criteria of 3% - 3 mm and 2% - 2 mm results in passing rate of 98% and 95% respectively for both film types irradiated with IMRT plan I. For IMRT plan II the gamma criteria of 3% - 3 mm show a passing rate of ~95–97% and gamma criteria of 2% - 2 mm show a passing rate of 84–91% depending on the film. In this analysis the doses <10% of the maximum dose were excluded from the calculation.

The gamma analysis failures occur typically on the border of the OSL images, which is also the region where the image reconstruction correction factors are the largest (Ahmed et al., 2016a). Because of the design of the laser-scanning reader (Fig. 1), the light collection...
efficiency drops radically from the center of the image. Nevertheless, this is a feature of the design of our experimental reader. Typical laser-scanning readers used in computed radiography capture the light using light guides from the entire length of the film, therefore, improving the collection efficiency from the borders of the film (Leblans et al., 2011).

The gamma analysis studies show that OSL films show good agreement with the TPS data and no effect of the magnetic field on the OSL response was observed in the current experimental conditions.

4. Conclusions and future developments

The tests using samples of Al,O3:C OSLD films (“point detectors”) and Al,O2:C and Al,O2:C,Mg OSLD films did not show evidence of influence of the 0.35 T magnetic field on the OSL results. The Al,O2:C point detectors showed accurate results, confirming the previous report from Spindeldreier et al. (2017) based on a regular linear accelerometer with the detectors irradiated within a magnet with fields up to 1.0 T. Results for different irradiation angles (0°, ±90°) in a simple geometry (Fig. 2a) showed deviations <1%, except for a repeated irradiation at 0°, which showed a deviation of 3%. For a more complex geometry (Fig. 2b), differences of up to 4% with the delivered dose were observed, but the variation with respect to the mean OSL response was ±2%. A larger spread in the response of the detectors within the same package (2–3%) was observed in comparison with previous results (Yukihara et al., 2005), but this could not be associated with the presence of a magnetic field, since similar results were obtained using a conventional LINAC. One should emphasize that these results refer to bare detectors packaged only with black tape to protect them from light and are not applicable to detectors inside a dosimeter casing containing air gaps.

The OSLD film results demonstrate the equivalence of the Al,O3:C and Al,O2:C,Mg films for the dose determination. As reported before, Al,O3:C has a higher OSL signal, but Al,O2:C,Mg shows better signal-to-noise ratio because of the higher concentration of fast luminescence centers (Ahmed et al., 2016b). Both films performed equivalently for the evaluation of IMRT plans. The failures in the gamma analysis are typical on the edge of the films, where large correction factors are required due to the reader design (light collection efficiency correction).

In summary, the results for point detectors indicate the reliability of the Al,O3:C OSLDs and its potential use for in vivo dosimetry in MRI-Linac system, even though online readout is not possible. Nevertheless, for small fields and high dose (up to 10 Gy) per fraction treatments, OSLDs could be a promising tool to verify the delivered dose in different points. The results on film detectors strongly support the use of the film for 2D dosimetry for geometrical complex dose distribution. Therefore OSLD films could be employed for MRI-Linac system QA as a comparable alternative to the radiographic films, with the potential advantage of reusability. Further investigation could be performed at higher dose level, in particular for dose range from 0.4 to 40 Gy for the applications such as stereotactic radiosurgery (SRS) and stereotactic body radiotherapy (SBRT).

The main drawback of the technique at the moment is the lack of commercial equipment for readout of the OSLD films. The laser scanning system described here and in previous publications (Ahmed et al., 2014) was developed as an experimental device for proof-of-principle demonstration, not as a blueprint for a commercial device. A commercial reader would more likely resemble the readers used in computed radiography (Leblans et al., 2011), but with optics and image reconstruction algorithm adapted for the Al,O3:C material. We hope that the results presented here will motivate further developments toward a practical, commercial system based on OSL for 2D dosimetry.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Dr. Cusumano, Dr. Placidi report personal fees due to speaker honorarium agreement from ViewRay, outside the submitted work.

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