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Dosimetric validation study of a flattening filter free SABR treatment by use of a normoxic PAG gel dosimeter with MRI readout

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Abstract. This paper describes clinical studies of the normoxic PAG gel dosimeter with MRI readout for validation of complex flattening filter free (FFF) treatment delivery techniques. Recently our department implemented the Elekta FFF technology for stereotactic ablative radiotherapy (SABR) treatments using dynamic conformal arc (DCAT) and volumetric arc therapy (VMAT). In this study 6MV FFF DCAT and VMAT plans were analysed using 3D gel dosimetry techniques and compared against standard clinical dosimetry QA tools. Some challenges with this validation study included high dose per fraction for SABR, MRI access time and $R_2$-dose calibration errors. A study of the dependency of the dose response on dose rate revealed insignificant dose rate dependence of the normoxic PAG dosimeter up to 20 Gy/min for both photon energies (6 MV and 10 MV).

1. Introduction

Three-dimensional dosimeters are of great interest in a progressive radiotherapy facility utilising complex and advanced treatments techniques such as high dose rate dynamic SABR. In our Centre, we recently introduced three-dimensional polymer gel dosimeters for encapsulating and validating 6MV FFF VMAT and DCAT treatments. Treatments of this nature, however, are difficult and complex to validate and mainstream quality assurance tools are often limited in their ability to satisfy clinical demands [1-7]. Three-dimensional polymer gel dosimeters offer significant advantages for validating steep 3D dose distributions of this complexity. This paper discusses some of the challenges encountered while using the normoxic PAG gel dosimeter [8, 9] in the clinical setting such as high dose short fractionation regimes, dose rate response and geometric and dosimetric accuracy. Clinical examples are presented for 6MV FFF VMAT and DCAT treatments planned using Monaco™ v 5.10.02 and delivered using the Elekta Agility™ head.

2. Methods and Materials

2.1. Phantom simulation and treatment planning

The gel container was initially filled with water and imaged using a Siemens Somatom™ Helical CT scanner. Our department uses the Monaco™ Monte Carlo treatment planning system. The 6MV FFF DCAT and VMAT patient plans were copied onto the phantom data set retaining segment shapes and monitor units using a 2 mm calculation grid with 1% statistical uncertainty in dose per plan. The resulting transverse dose distributions were exported with 2 mm centre slice spacing separation to compare with the measured gel dose distributions.
2.2. Dosimeter manufacture
The normoxic PAG dosimeters were manufactured on the bench top in a fume cupboard using a method described elsewhere [5]. The formulations consisted of 3.5% \(N,N\)-methylene-bis-acrylamide (bis), 3.5% acrylamide (AA), 5% gelatine, 5 mM tetrakis (hydroxymethyl) phosphonium chloride (THPC), 1 mM hydroquinone (HQ) and 88% deionised \(\text{H}_2\text{O}\).

2.3. Phantom & calibrations vials
In each study the liquid dosimeter was poured into eleven 15 ml Pyrex\textsuperscript{TM} glass calibration vials and a 3 litre container of similar type that has been used elsewhere [10] (see Figure 2). The dosimeter was left on the bench top to cool for an hour and then subsequently placed in a refrigerator to set overnight.

2.4. Phantom and calibration vial irradiation
Temperature control measures were implemented before irradiation to ensure the dosimeters were in equilibrium with the ambient air temperature. The gel phantom was placed on the treatment couch at the linac iso-centre and irradiated according to the patient’s treatment plan. The calibration vials were irradiated to different known doses in water according to the TRS-398 protocol [11].

2.5. MRI readout
After equilibrating with the ambient air temperature, the dosimeters were imaged using a Siemens Avanto 1.5T clinical MRI scanner with a head coil. An interleaving multi-echo-pulse sequence consisting of 16 echoes with TE of 40 ms, TR of 3240 ms, FOV 128 x 128 mm\(^2\), 2 mm slice thickness, pixel bandwidth of 130, 1 acquisition with 21 slices separated by 2 mm centres was used resulting in an imaging time of 42 minutes [12]. Due to MRI access constraints only the minimal imaging parameters were used. It was determined that a TE of 40ms with 16 echoes was sufficient to cover the range of \(R_2\)-dose response within the dosimeter.

2.6. Processing and analysis
MRI images were processed using in-house software created in Matlab\textsuperscript{TM}. \(R_2\) maps of each axial slice in the phantom were calculated and converted to dose maps using the \(R_2\)-dose response calibration curve generated from the calibration vials. The dose maps were imported into the SunNuclear Patient Software\textsuperscript{TM} v6.2 for gamma map analysis with the TPS’s dose distributions. Only the normalised/geometric dose distribution was studied in these examples. Gamma maps were subsequently assessed using relative mode in the SNC Patient software with a pass/fail criterion of 3%/3 mm and a 10% lower dose threshold.

2.7. Clinical QA measurement using SNC ArcCheck and CC04 chamber
Both DCAT and VMAT plans were measured using our standard clinical QA dosimetry tools for comparison purposes which included the SNC ArcCheck\textsuperscript{TM} and a point dose measurement using a CC04 ionisation chamber at the isocentre.

2.8. FFF Dose rate study
Using the calibration vials a dose rate dependence study was performed to assess the response of the normoxic PAG dosimeter for FFF beams up to a maximum dose rate of 2000 cGy/min for a dose of 5Gy at each dose rate. \(R_2\)-dose response was plotted as a function of dose rate.
3. Results and Discussion

3.1. \(R_2\)-dose response
Figure 1 shows the \(R_2\)-dose response curves for the two batches of gels made in this clinical study. The \(R_2\)-dose sensitivities were 0.31029 s\(^{-1}\)Gy\(^{-1}\) for the DCAT study and 0.29175 s\(^{-1}\)Gy\(^{-1}\) for the VMAT study both with linear regions that extended up to 5 Gy.

3.2. Gel phantom measurement compared to TPS with gamma analysis
Figure 2 shows the irradiated DCAT gel phantom along with the MRI dose map. Only central axis transverse dose maps are shown in figures 3 and 4 for each delivery technique compared against the TPS with the associated gamma values. Adjacent to each dose map comparison is a profile taken through the central axis of the dose distribution and the associated gamma values for the above criteria. In the transverse plane 21 slices at 2 mm separation can be analysed and by interpolation, 128 sagital and coronal dose planes are available to analyse at 1 mm centre separations, which allows the dose distribution in each plane to be assessed.

The identified errors in \(R_2\) in the phantom are potentially related to reasons discussed elsewhere, such as, over response of \(R_2\) in a large phantom volume compared with relatively small calibration vials [13]. Normalisation was performed on the central axis with a small shift applied to locate a better overall fit of the dose distribution. Off-axis dose distributions were also assessed, however due to the limited scope within this abstract these will not be covered in this article.

3.2.1. DCAT plan. The overall pass rate for the central axis slice was 93.6% with 776 points failing the criteria and 11388 passing. No gamma score was above 2 for this dose plane.

![Figure 1. \(R_2\)-dose response of the two batches of normoxic PAG gel.](image1)

![Figure 2. Irradiation of the normoxic PAG gel dosimeter with the associated colour rendered MRI dosemap.](image2)

![Figure 3. Gamma map analysis for DCAT plan with central axis profile.](image3)
3.2.2. VMAT plan. The overall pass rate for the central axis transverse slice was 87.7% with 1383 points failing the criteria and 9865 passing. The gamma scores were all below 2 for this dose plane.

![Gamma map analysis for VMAT plan with central axis profile.](image)

3.3. Clinical QA measurement using SNC ArcCheck and CC04 ionisation chamber
The VMAT plan passed the specified gamma criteria at 97.6% with 9 points failing and 360 passing. The highest gamma score was 2.45. The dose at the isocentre measured -2.2% below the TPS value. The DCAT plan passed the specified gamma criteria at 95.5% with 21 points failing and 441 passing. The highest gamma score was 2.7. The point dose measured 2.4% above the TPS value.

3.4. FFF dose rate study
Figure 5 shows the $R_2$- response as a function of dose rate for a dose of 5Gy. The plot shows a weak dependence with increasing dose rate with a linear fit having a gradient of $-6 \times 10^{-5}$ s$^{-1}$cGy$^{-1}$min for 6MV and $-9 \times 10^{-5}$ s$^{-1}$cGy$^{-1}$min for 10MV.

4. Conclusion
There are many challenges involved in setting up a gel dosimetry program [14-16] using MRI [17-23]. Expertise, time and access constraints are limiting factors in imaging optimization. Clinical requirements dictate that for short fractionation high dose regimes that the geometric and dosimetric parameters of a plan are well known and within tight tolerances. In this study, due to an $R_2$ over response in the dosimeter only the normalised dose distribution was studied. The errors in $R_2$ are potentially related to reasons discussed elsewhere [13]. While the normoxic PAG dosimeter has highly favourable characteristics for radiotherapy applications, it has a limited useful dose range [24] which is problematic for SABR doses. A typical fractionation regime would be 10Gy/fx, however when calculated on the gel phantom doses can be in excess of 20Gy. Ideally a gel will receive doses within the range of its optimal dose resolution [25]. The normoxic PAG dosimeter manufactured in this study exhibited a weak dose rate dependence at FFF dose rates and further work should be conducted to fully characterise this observation. Further development work will continue on our dosimetric and calibration techniques for high dose high dose rate SABR fractionation regimes.

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