A new dosimeter formulation for deformable 3D dose verification

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Abstract. We present the characteristics of a new silicone-based radiochromic dosimeter containing the leuco-malachite green (LMG) dye. The dose response as well as the dose-rate and photon-energy dependence of the dosimeter were characterized. To optimise the dose response, different concentrations of the chemical components were investigated. The dose response was found to decrease exponentially as a function of time after irradiation. A cylindrical dosimeter was produced and irradiated with a volumetric modulated arc therapy plan; the standard deviation between measured and calculated dose was 5% of the total dose.

1. Introduction

The increasing complexity of radiotherapy demands dose verification in three dimensions with high spatial resolution [1]. Gel dosimeters capable of performing these measurements include polymerizing and radiochromic dosimetry [2, 3]. Radiochromic dosimeters have been shown to be well suited for readout with optical computed tomography (CT) [4]. The dose response in radiochromic micelle dosimeters is caused by the dye leuco-malachite green (LMG) [5]. LMG is a nonpolar molecule, which restricts its use with hydrogels for forming a 3D dosimeter. Micelle dosimeters successfully avoid this restriction by encapsulating the dye in micelles which can be dissolved in the hydrogel. The dose response of the micelle dosimeter has been restricted by its chemistry and has been shown to be dose-rate dependent [5, 6]. LMG is also used in the commercial Presage® dosimeters, in this case embedded in a polyurethane polymer. In the current study, silicone has been investigated as a host matrix for LMG dissolved in chloroform, in order to create a 3D dosimeter with new clinical applications. The dose response, the dose-rate and energy dependence have been investigated in photon beams. The characteristics of the host material open potentials for the dosimeter to be molded into anthropomorphic phantoms and for subsequent mechanical manipulation (compression, bending etc.) during irradiation.

2. Materials and methods

2.1. Fabrication

The new radiochromic dosimeter that was investigated in this study uses the commercially available Dow Corning SYLGARD® 184 Silicone Elastomer Kit as a host material for the active component LMG, which was dissolved in chloroform. The curing agent and the silicone elastomer were used in a 1:10 weight ratio. LMG dissolved in chloroform was first mixed with the curing agent and subsequently with the silicone elastomer. Air bubbles were removed from the dosimeter by use of a

vacuum desiccator in two steps; before and after being poured into the containers. The containers were standard PMMA cuvettes ($1 \times 1 \times 4.5$ cm^3) and a cylindrical container of 15 cm height and 15 cm diameter. The dosimeters were covered with aluminium foil to avoid light pollution and left to cure at room temperature.

The cylindrical dosimeter and the batch which was investigated for dose-rate and energy dependence contained 0.4 mM LMG and 85 mM chloroform, and were allowed to cure for 48 hours. Batches of varying LMG and chloroform concentrations were produced to investigate the dose response. Four batches with chloroform concentration of 100 mM and LMG concentrations of 0.2 mM, 0.4 mM, 0.6 mM and 1.0 mM were produced. Three batches with LMG concentration of 0.4 mM and chloroform concentrations of 80 mM, 150 mM and 200 mM were also produced. These batches were allowed to cure for 24 hours.

2.2. Irradiation

The dosimeters were irradiated with a Varian linear accelerator at Aarhus University Hospital. The cuvettes were irradiated with 10×10 cm^2 photon fields of 6 MV and 15 MV beam quality, at a dose-rate of 600 MU/min, as well as at dose-rates of 100, 200 and 400 MU/min with 6 MV. The cuvettes were placed between two 5 cm slabs of solid water in SSD 94.5 cm.

A cylindrical dosimeter was irradiated with a volumetric modulated arc therapy (VMAT) plan, which delivered a dose distribution of 3 Gy in the shape of a cone in the inferior end of the dosimeter. From the middle to the superior end, the dosimeter was irradiated with a cylindrically-shaped dose gradient from 5 Gy to 1 Gy in steps of 1 Gy, and finally 0 Gy and 1 Gy in the superior end. The irradiation consisted of three fractionations with a maximum of 5 Gy in each, giving a total of 15 Gy.

2.3. Readout and data analysis

The optical densities of the cuvettes were measured with a spectrophotometer (Helios Alpha, Thermo Spectronic) at 624 nm. A pre-scan was performed a couple of hours before irradiation and repeated post-scans were performed during the days following irradiation. The change in optical density caused by the irradiation was found by subtracting the pre-scan from the post-scans. The optical response (i.e. the optical absorptivity *versus* the irradiated dose) was fitted to a linear equation, and the dose response was found as the slope of the fit. The change in dose response with time was fitted to an exponentially decreasing function with an offset.

The cylindrical dosimeter was scanned with an OCTOPUS IQ optical-CT scanner (MGS Research, Inc., Madison, CT, USA) approximately four hours before irradiation and post-scanned three hours after irradiation. The data analysis was performed as in [7] but employing a direct voxel-to-voxel correlation between the VMAT plan and the CT measurement.

3. Results

The optical response was highest for the high-energy beam: At 10 Gy the optical response was approximately 2% higher for the cuvette irradiated with a 15 MV beam compared to that irradiated with a 6 MV beam. The energy dependence increased linearly with dose, reaching 9% at 60 Gy. A dose-rate dependence was also found; from 600 MU/min to 100 MU/min the dose response increased by 32 ± 1 % relative to that at 600 MU/min.

The optical responses approximately one hour after irradiation for the batches with different LMG concentrations are shown in figure 1. The dose response was fitted by a linear function, and the slopes were higher for the batches with high LMG concentration. However, the dose response did not increase regularly with concentration, as seen in figure 2. The same trend was observed for the batches with increasing chloroform concentration. The response was linear up to 60 Gy at all post-scans.

The post-scans performed over six days revealed that the dose response of all batches decreased exponentially in time, as shown in figure 3. The decay time did not depend on the concentration of either LMG or chloroform. The zero-dose optical response (i.e. the auto oxidation) increased with time.

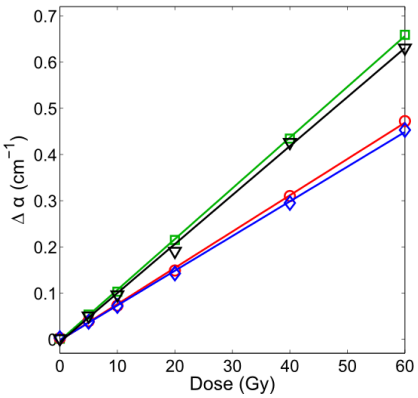

Figure 1. The optical response, Δα, for batches with 100 mM chloroform and LMG concentrations of 0.2 mM (red circles), 0.4 mM (blue diamonds), 0.6 mM (black triangles) and 1.0 mM (green squares).

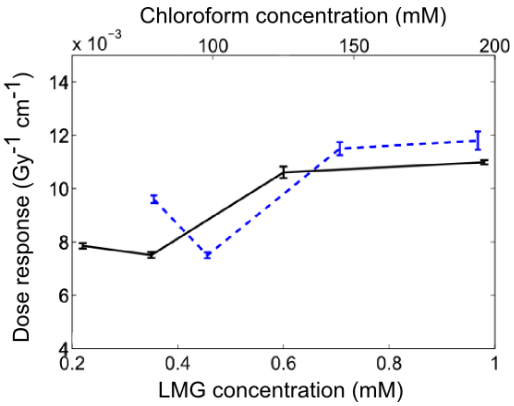

Figure 2. The dose response one hour after irradiation as a function of LMG (full) and chloroform (dashed) concentrations. Error bars from the linear fits to the optical response are shown.

The VMAT dose distribution measured in the cylindrical dosimeter reproduced the features of the plan successfully, as seen in figure 4. In a voxel to voxel analysis of the full dosimeter, the standard deviation between measured and calculated dose was 5% of the total dose.

4. Discussion

The new silicone-based dosimeter showed a significant dose-rate dependence, as well as a small energy dependence. Further investigations at different concentrations of LMG and chloroform are needed to determine if these effects can be minimized. Dose-rate dependencies have for other dosimeters to some extent been minimized by pre-irradiating the dosimeter with a low dose [5]. The high dose response makes it possible to optimize the dosimeter for the lowest dose-rate and energy dependence.

Measurements at higher concentrations are needed to verify whether a saturation of the dose response is observed at the highest LMG and chloroform concentrations in figure 2. The dose responses faded quickly in time and fitted exponentially decaying functions very well. This facilitates determining the dose response at any time, provided that the decay function is well known. The dose response was significantly higher than in micelle dosimeters containing the same dye and solvent concentrations, reported to be 3.5×10^{-3} Gy^{-1} cm^{-1} in [6] with 0.37 mM LMG and 80 mM chloroform. The highest dose response observed in this study was 1.2×10^{-2} Gy^{-1} cm^{-1} with 0.4 mM LMG and 200 mM chloroform. This is comparable to the dose response of Presage®, which we have measured to

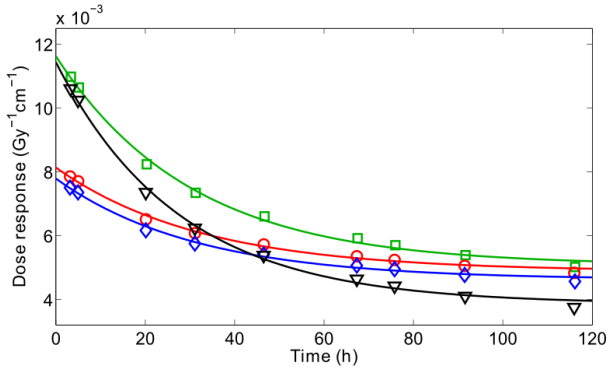

Figure 3. The dose response decayed exponentially with time after irradiation for all LMG concentrations (symbols as in figure 1).

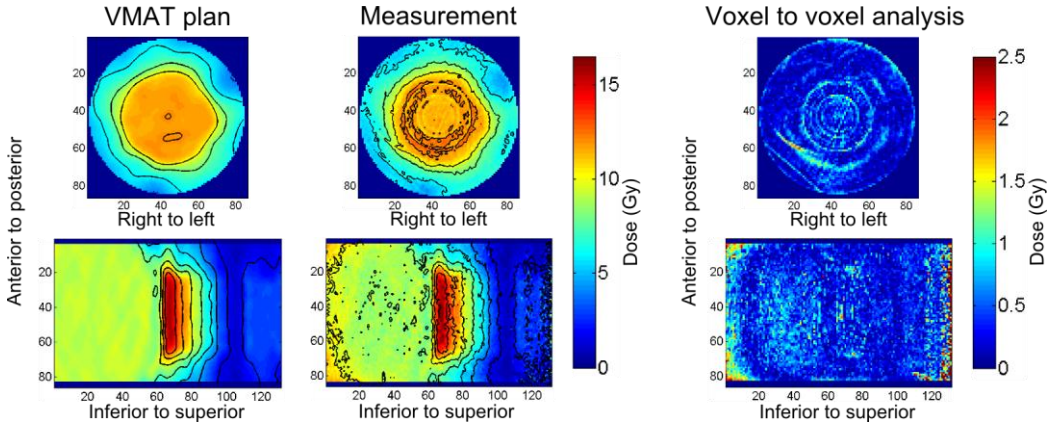

Figure 4. First 3D results with the new silicone-based dosimeter. The upper row shows the transversal plane through the high-dose region (slice 76) in the middle of the dosimeter, and the lower row shows the coronal plane through the central part of the dosimeter. Isocurves are plotted in the calculated VMAT plan and in the results from the optical CT measurement (1 mm^3 voxels) from 2 Gy to 14 Gy with 2 Gy intervals. The final column shows a voxel to voxel analysis of the dose difference between plan and measurement.

2.3×10^{-2} Gy^{-1} cm^{-1} [8]. The data seem to indicate that the dose response of the silicone dosimeter could be increased even further by increasing the dye and chloroform concentrations. Unfortunately, significant colouring of the dosimeters before irradiation was observed, which eventually will restrict the dynamical range of the dosimeter-scanner system.

The dosimeter reproduced the 3D distribution of a challenging VMAT plan with high dose gradients, which shows that it has great potential for use as a clinical dosimeter. The production of the dosimeters is straightforward and fast and requires few utilities. The consistency of the dosimeter was such that it could be used as a compressible dosimeter. This would be useful for studying, e.g., the impact of heart and lung movements on a delivered dose distribution. The dosimeter is solid enough to be handled without a container, and the dosimeter could therefore be moulded into the shape of organs. This would also significantly reduce the image artefacts close to the walls of the dosimeter, caused by light refraction at the boundary between container and dosimeter. A further analysis of the 3D properties of the dosimeter will not be provided here, as problems with the refractive-index-matching liquid created artefacts in the measurement that can easily be avoided in future studies.

5. Conclusion

This first study of the LMG/silicone dosimeter shows that it has significant potential for use as a radiochromic dosimeter in clinical practise, but that further investigations and development is necessary. A high dose response is conceivable, presumably by applying higher LMG and chloroform concentrations. Silicone elastomer has physical characteristics that introduce the possibility of moulding the dosimeter into the desired shape and manipulating the dosimeter mechanically during irradiation to mimic clinically relevant deformation of organs.

6. References

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